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Power System - I

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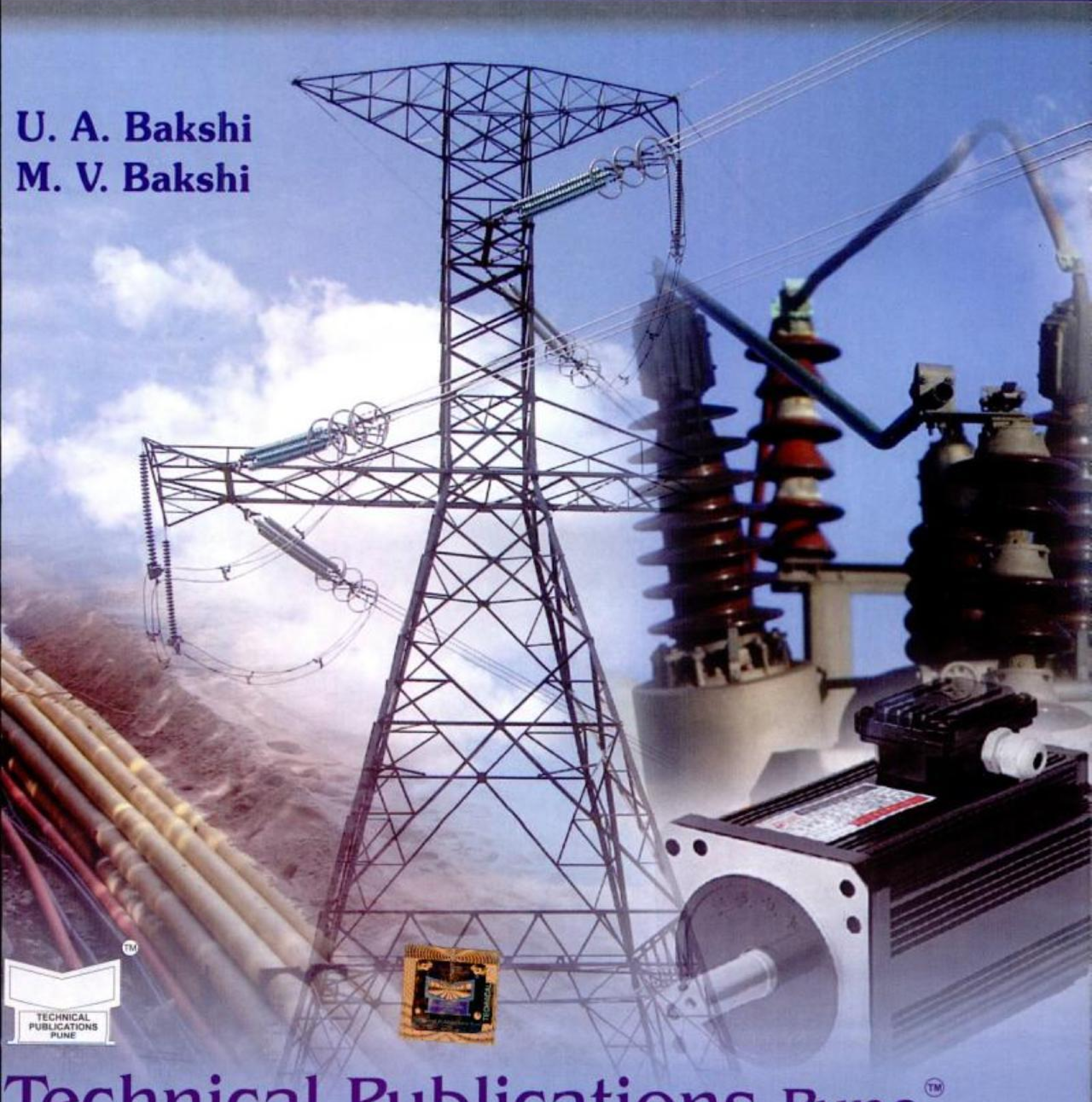

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Syllabus (Power System - I)

Unit-I (Chapter- 1)

An overview of Electrical Energy Generation

General background, Structure and components of power network. Power generation - Introduction to conventional, Non-conventional and distributed generation, Effect of transmission voltage on power system economy. Selection of size of feeder. Comparison of isolated versus interconnected power system. Problems associated with modern large interconnected power system. Power plant economics - Load curves, Base load, Peak load, Load factor, Demand factor, Diversity factor, Capacity factor, Utilization factor, Cost of electricity, Capital cost, Fuel and operation cost.

Unit-II (Chapters- 2, 3)

Transmission Line Components and Underground Cabling

Inductance resistance and capacitance of transmission line, Calculation of inductance for 1-phase and 3-phase, Single and double circuit line, Concept of GMR and GMD, Symmetrical and asymmetrical conduction configuration, Calculation of capacitance for 2 wire and 3 wire systems, Effect of ground or capacitance, Capacitance calculation for symmetrical and asymmetrical 1-phase and 3-phase, Single and double circuit line, Charging current, Transposition of line, Composite conductor, Skin and proximity effect, Bundle conductor.

Underground Cable

Comparison of cables and overhead transmission lines, Classification of cables, Requirement of cable construction, Capacitance of single and multi-core cable, Economic core diameter, Dielectric stress in cable, Grading of cables, Ionization of heating of cables, Phenomena of dielectric losses and sheath loss in cables, Thermal resistance of cables.

Unit-III (Chapters- 4, 5)

Transmission Systems and Performance of Transmission Line

Various systems of transmission, Effect of system voltage, Comparison of conductor materials required for various overhead systems.

Short, medium and long transmission line and their representation, Nominal T, Nominal π, Equivalent T and equivalent π, Network models, ABCD constants for symmetrical and asymmetrical network, Mathematical solution to estimate regulation and efficiency of all types of lines.

Surge impedance, Loading, Interpretation of long line equation and its equivalent equation. Tuned power lines. Power flow through transmission line, Circle diagram, Method of voltage control, Static and rotating VAR generator, Transformer control.

Unit-IV (Chapters- 6, 7)

Insulator and Mechanical Design

Types of conductors used in overhead transmission line, Types of line supports and towers, Distribution of conductors over transmission towers, Spacing between conductors, Length of span and sag-tension calculation for transmission line, Wind and ice loading, Support of line at two different levels, String chart, Sag template, Stringing of conductor, Vibration and vibration dampers.

Insulator

Materials used for transmission line insulations, Types of insulator for overhead transmission line failure of insulator, Voltage distribution of suspension insulator, String efficiency, Shielding and grading.

Unit-V (Chapter- 8)

Voltage Control and Distribution System

AC single phase, 3 phase, 3 wire and 4 wire distribution, Kelvin's law for most economical size of conductor substation layout showing substation equipment, Bus bar single bus bar and sectionalized bus bar, Main and transfer for bus bar system, Sectionalized double bus bar system, Ring mains.

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1

Power Generation

1.1 Introduction

The energy is neither be created nor be destroyed but it can be converted from one form to another. The generation of an electrical energy is nothing but the conversion of various other forms of energy into an electrical energy. The various energy sources which are used to generate an electrical energy on the large scale are steam obtained by burning coal, oil, natural gas, water stored in dams, diesel oil, nuclear power and other nonconventional energy sources. The electrical power is generated in bulk at the generating stations which are also called power stations. Depending upon the source of energy used, these stations are called thermal power station, hydroelectric power station, diesel power station, nuclear power station etc.

This generated electrical energy is demanded by the consumers. Hence the generated electrical power is to be supplied to the consumers. Generally the power stations are located too far away from the town and cities where electrical energy is demanded. Hence there exists a large network of conductors between the power stations and the consumers. This network is broadly classified into two parts.

1. Transmission 2. Distribution

In this chapter, let us discuss the basic elements of a typical transmission and distribution scheme. The chapter also includes the various distribution systems and related calculations. At the end it includes discussion on EHV AC and HVDC transmission.

1.2 Structure of Electrical Power System

The flow of electrical power from the generating station to the consumer is called an electrical power system or electrical supply system. It consists of the following important components :

1. Generating station
2. Transmission network
3. Distribution network

All these important networks are connected with the help of conductors and various step up and step down transformers. A typical transmission and distribution scheme is shown in the Fig. 1.1.

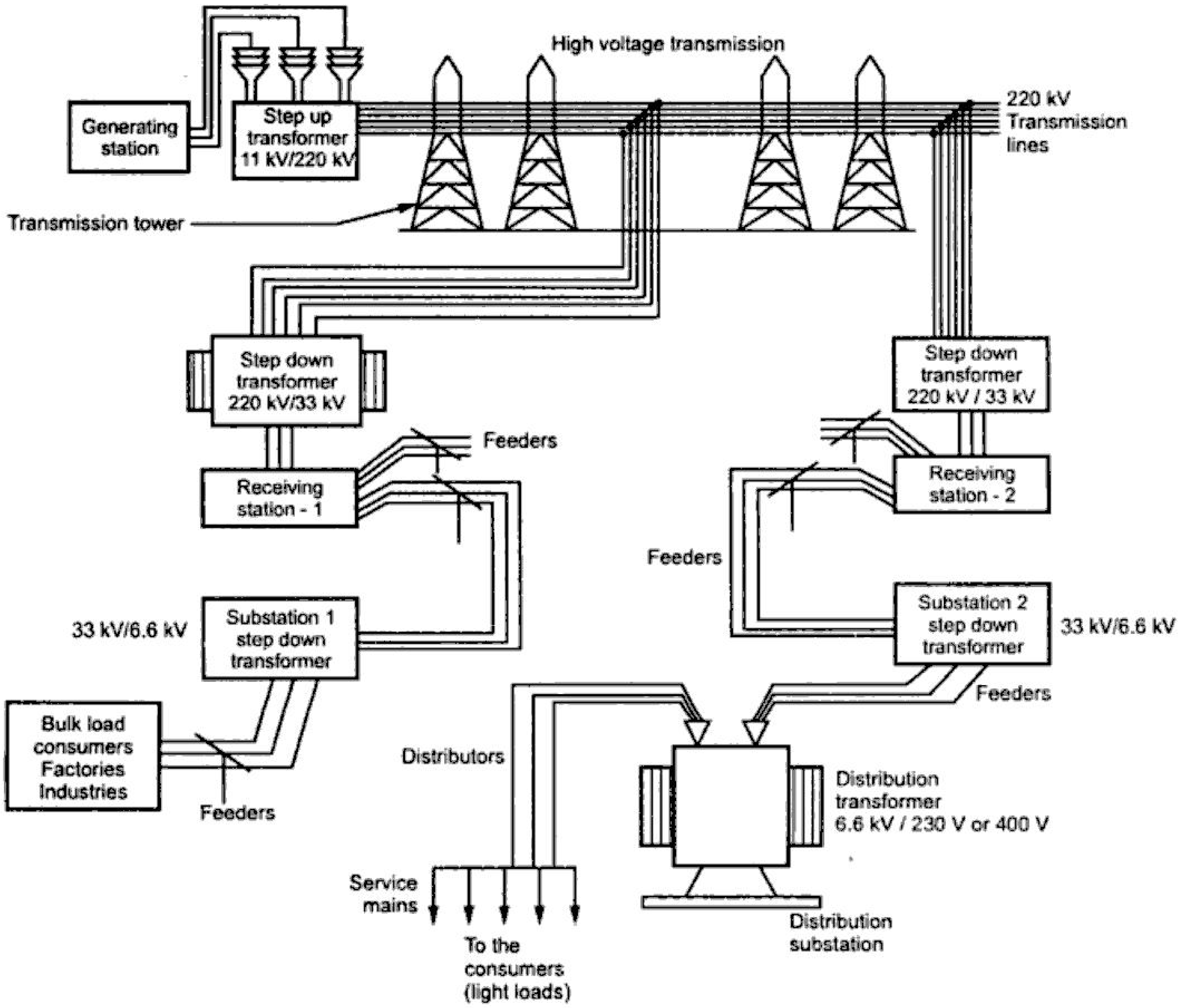

High voltage transmission
Generating station
Step up transformer 11 kV/220 kV
220 kV Transmission lines
Transmission tower
Step down transformer 220 kV/33 kV
Step down transformer 220 kV / 33 kV
Feeders
Receiving station - 1
Receiving station - 2
Feeders
33 kV/6.6 kV
Substation 1 step down transformer
Substation 2 step down transformer
33 kV/6.6 kV
Feeders
Bulk load consumers Factories Industries
Feeders
Distributors
Distribution transformer 6.6 kV / 230 V or 400 V
Service mains
To the consumers (light loads)
Distribution substation

Fig. 1.1 Schematic representation of a typical transmission distribution scheme

A scheme shows a generating station which is located too far away from cities and towns. It is generating an electrical power at 11 kV. It is required to increase this level for the transmission purpose. Hence a step up transformer is used which steps up the voltage level to 220 kV. This level may be 132 kV, 220 kV or more as per the requirement.

Then with the help of **transmission lines** and the towers, the power is transmitted at very long distances. Design of the transmission lines is based on the factors like transmission voltage levels, constants like resistance, reactance of the lines, line performance, interference with the neighbouring circuits etc. Its mechanical features are strength of the supports, sag calculations, tension etc. Transmission of power by the overhead lines is very much cheaper. Similarly the repairs also can be carried out comparatively more easily. The transmission is generally along with additional lines in parallel. These lines are called **duplicate lines**. Thus two sets of three phase lines work in parallel. This ensures the continuity during maintenance and also can be used to satisfy future demand. The power is then transmitted to the receiving station via step down transformer. This transformer is 220/33 kV or 220/22 kV transformer.

The power is then transmitted to the substations. A substation consists of a step down transformer of rating 33 kV to 6.6 kV or 3.3 kV. The transfer of power from receiving station to the substation is with the help of conductors called **feeders**. This is called **secondary transmission**.

From the substations, power is distributed to the local distribution centres with the help of **distributors**. Sometimes for bulk loads like factories and industries, the distributors transfer power directly. For the light loads, there are distribution centres consisting of distribution transformers which step down the voltage level to 230 V or 400 V. This is called **primary distribution**. In the crowded areas like cities, overhead system of bare conductors is not practicable. In such cases insulated conductors are used in the form of underground cables, to give supply to the consumers. These cables are called **service mains**. This is called **secondary distribution**.

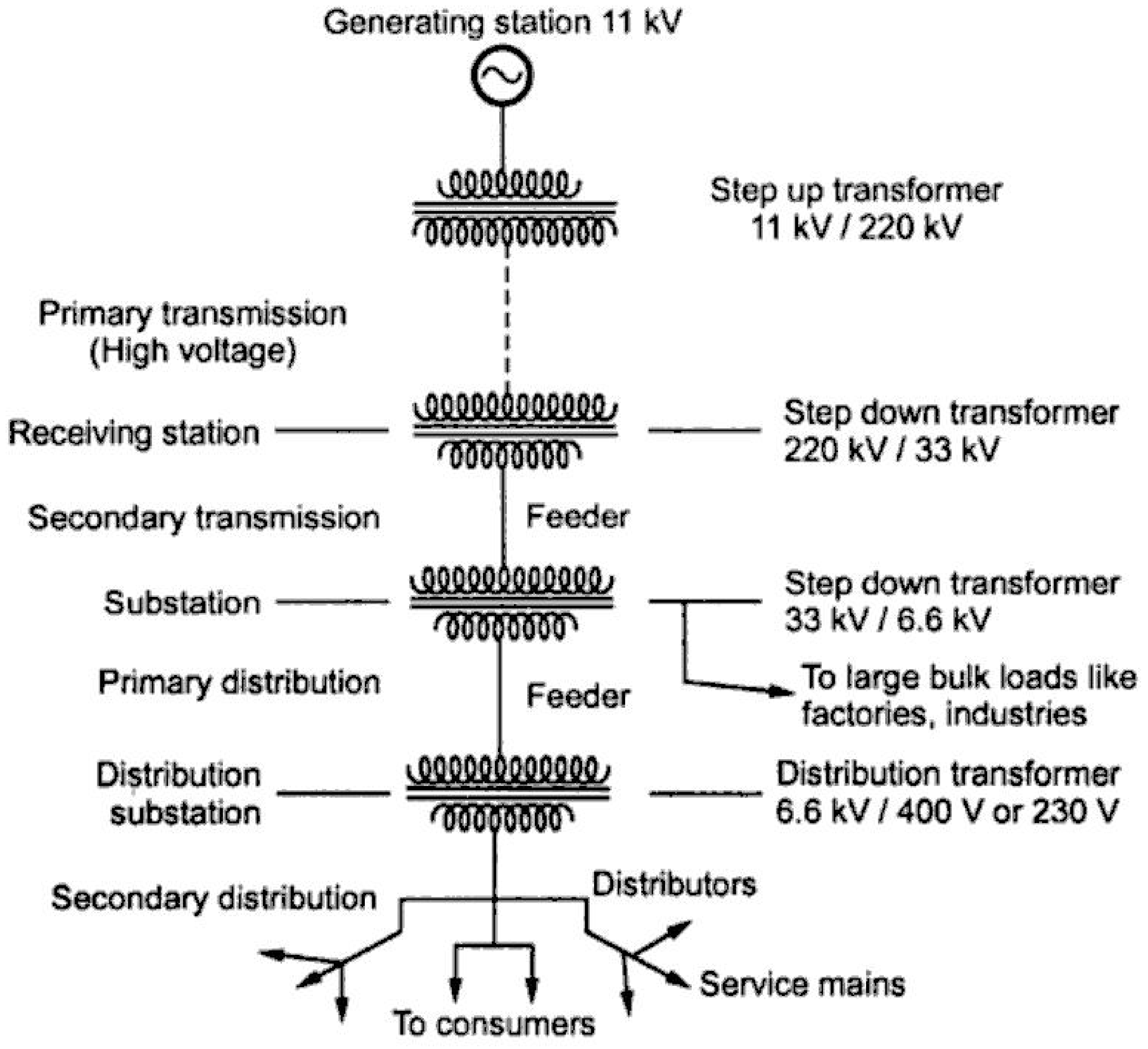


Fig. 1.2 Line diagram of a typical transmission distribution scheme

This is the complete flow of an electrical power from the generating station to the consumer premises.

Let us study the line diagram of such a typical scheme of transmission and distribution and discuss the various components and voltage levels at the various stages in detail. The Fig. 1.2 shows the line diagram of a typical transmission and distribution scheme.

At the generating station, an electrical power is generated with the help of three phase alternators running in parallel. In the scheme shown, the voltage level is 11 kV but the voltage level may be 6.6 kV, 22 kV or 33 kV depending upon the capacity of the generating station. After the generating station, actual transmission and distribution starts. The overall scheme can be divided into four sections which are,

1. **Primary transmission :** It is basically with the help of overhead transmission lines. For the economic aspects, the voltage level is increased to 132 kV, 220 kV or more, with the help of step up transformer. Hence this transmission is also called **high voltage transmission**. The primary transmission uses 3 phase 3 wire system.
2. **Secondary transmission :** The primary transmission line continues via transmission towers till the receiving stations. At the receiving stations, the voltage level is reduced to 22 kV or 33 kV using the step down transformer. There can be more than one receiving stations. Then at reduced voltage level of 22 kV or 33 kV, the power is then transmitted to various substations using overhead 3 phase 3 wire system. This is secondary transmission. The conductors used for the secondary transmission are called feeders.
3. **Primary distribution :** At the substation the voltage level is reduced to 6.6 kV, 3.3 kV or 11 kV with the help of step down transformers. It uses three phase three wire underground system. And the power is further transmitted to the local distribution centres. This is primary distribution, also called high voltage distribution. For the large consumers like factories and industries, the power is directly transmitted to such loads from a substation. Such big loads have their own substations.
4. **Secondary distribution :** At the local distribution centres, there are step down distribution transformers. The voltage level of 6.6 kV, 11 kV is further reduced to 400 V using distribution transformers. Sometimes it may be reduced to 230 V. The power is then transmitted using distributors and service mains to the consumers. This is secondary distribution, also called low voltage distribution. This uses 3 phase 4 wire system. The voltage between any two lines is 400 V while the voltage between any of the three lines and a neutral is 230 V. The single phase lighting loads are supplied using a line and neutral while loads like motors are supplied using three phase lines.

1.2.1 Components of Distribution

The distribution scheme consists of following important components.

1. **Substation :** Transmission lines bring the power upto the substations at a voltage level of 22 kV or 33 kV. At the substation the level is reduced to 3.3 kV or 6.6 kV. Then using feeders, the power is given to local distribution centres.

2. **Local distribution station :** It consists of distribution transformer which steps down the voltage level from 3.3 kV, 6.6 kV to 400 V or 230 V. Then it is distributed further using distributors. This is also called **distribution substation.**
3. **Feeders :** These are the conductors which are of large current carrying capacitor. The feeders connect the substation to the area where power is to be finally distributed to the consumers. No tappings are taken from the feeders. The feeder current always remains constant. The voltage drop along the feeder is compensated by compounding the generators.
4. **Distributors :** These are the conductors used to transfer power from distribution centre to the consumers. From the distributors, the tappings are taken for the supply to the consumers. The voltage drop along the distributors is the main criterion to design the distributors.
5. **Service mains :** These are the small cables between the distributors and the actual consumer premises.

The interconnection of feeders, distributors and service mains is shown in the Fig. 1.3.

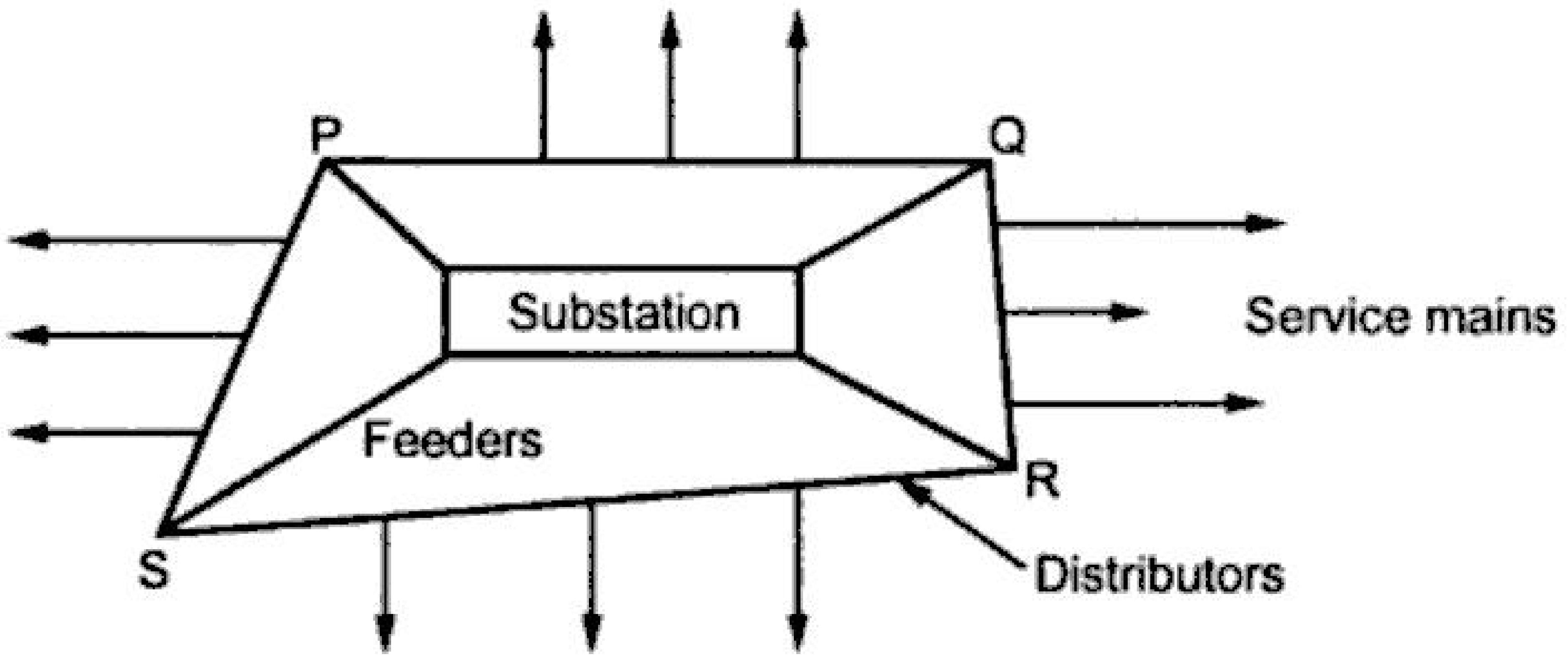


Fig. 1.3

There is no tapping on feeders. PQ, QR, RS and PS are the distributors which are supplied by the feeders. No consumer is directly connected to the feeder. The service mains are used to supply the consumers from the distributors. Tappings are taken from the distributors.

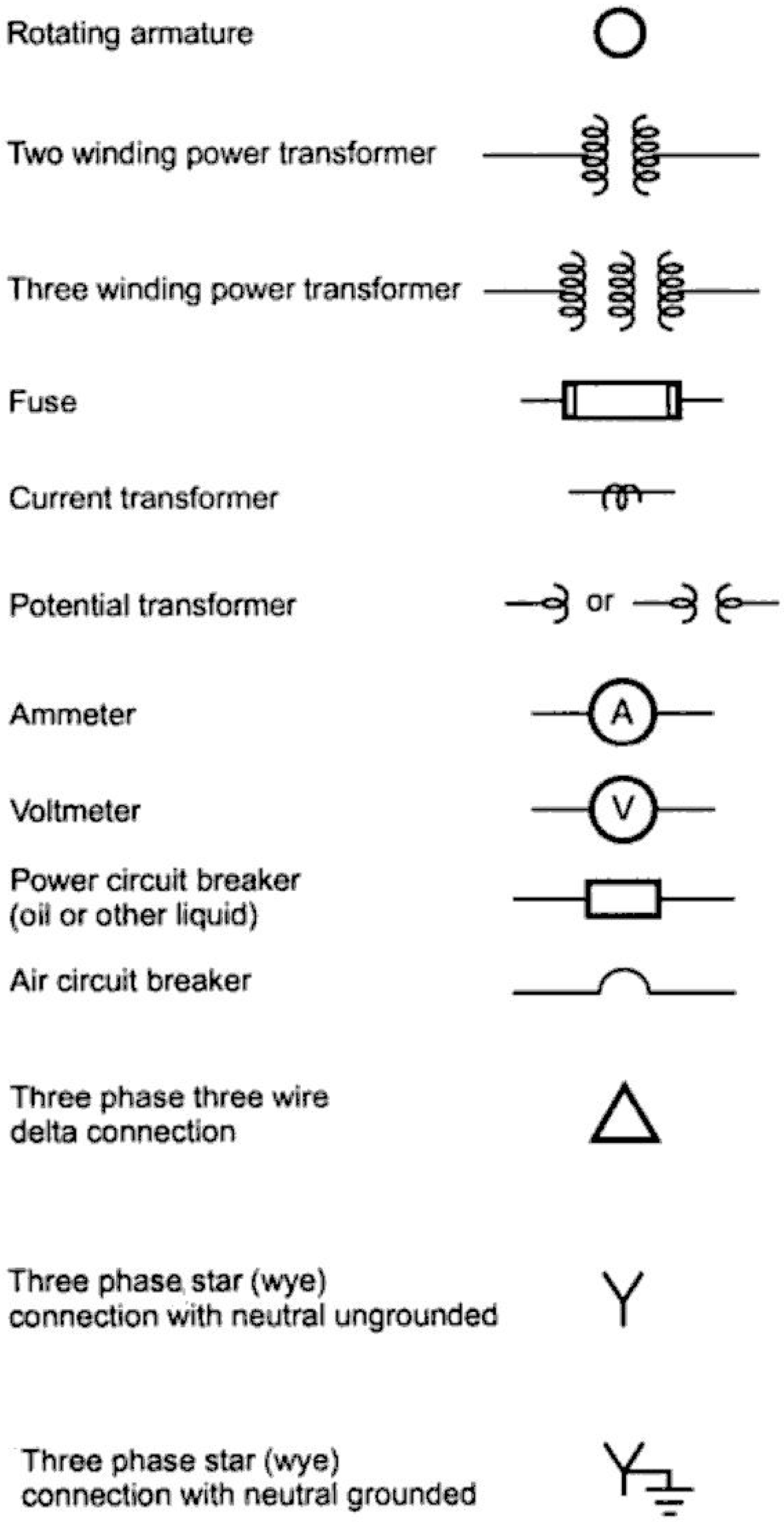
1.3 Single Line Diagram of Power System

The different elements of power systems are always required to be connected with each other so that the complete power system can be modelled. The supply system is normally three phase balanced system so while representing the system one of the three lines is shown with return through neutral. The representation of all three lines with neutral return is rarely required in practice. The representation of all power system elements along with their interconnections is done with the help of single line diagram of the system.

The single line diagram can still be simplified by excluding the completed circuit through the neutral and the components are represented by their standard symbols rather than by their equivalent circuits. The circuit parameters are not shown while the transmission line is indicated by a single line between its two ends.

Key Point : *Thus the single line diagram is nothing but the simplified representation of power system components with each other, with each component represented by its symbol.*

The standard symbols used for drawing single line diagram of a power system are shown below.


Rotating armature
Two winding power transformer
Three winding power transformer
Fuse
Current transformer
Potential transformer
or
Ammeter
A
Voltmeter
V
Power circuit breaker (oil or other liquid)
Air circuit breaker
Three phase three wire delta connection
Three phase star (wye) connection with neutral ungrounded
Three phase star (wye) connection with neutral grounded

The significant information about the power system can be obtained in concise form from the single line diagram. The various features of the system are different based on the problem that is considered. The information to be included in the single line diagram is dependent on the purpose for which the diagram is drawn.

The location of circuit breakers and relays is not important when one undergoes load flow study of the system. In such case they are not shown on the single line diagram and the intension of single line diagram in such case is to study the load flow.

But if it is required to determine the stability of power system under transient conditions during fault then the role of relays and circuit breakers is vital. This is because the stability under transient conditions due to fault is dependent on speed with which relays and circuit breakers operate to isolate the faulty part. Under such case, information related to circuit breakers must be included in the single line diagram as it is important.

The single line diagram may also include the information about current and potential transformers which are either connected to the relays or are used for metering purpose. Hence it can be seen that the information obtained from single line diagram varies with its purpose and problem. It is also dependent upon the standard practice of the company which is preparing these single line diagrams.

The various organisations such as ANSI (American National Standards Institute), IEEE (Institute of Electrical and Electronics Engineers) have published standard symbols for drawing electrical diagrams. It is expected that these symbols must be used in all the diagrams everywhere in order to have simplicity, clarity and uniformity. If someone is not consistent with these diagrams and symbols then it is better to represent the machine with its basic symbol followed by information on its type and rating.

The point at which the system is connected to ground is important as it helps in determining the amount of current flowing when an unsymmetrical fault occurs on the system involving ground. The current to the ground is limited by connecting either a resistor or reactor between the neutral of ⅄ and ground. The correct symbol for resistance or inductance should be added in the diagram when grounded ⅄ connected transformer is shown. Most transformer neutrals in transmission systems are solidly grounded. The generator neutrals are normally grounded through comparatively higher resistances or sometimes through inductance coils.

The Fig. 1.4 shows a single line diagram of a simple power system.

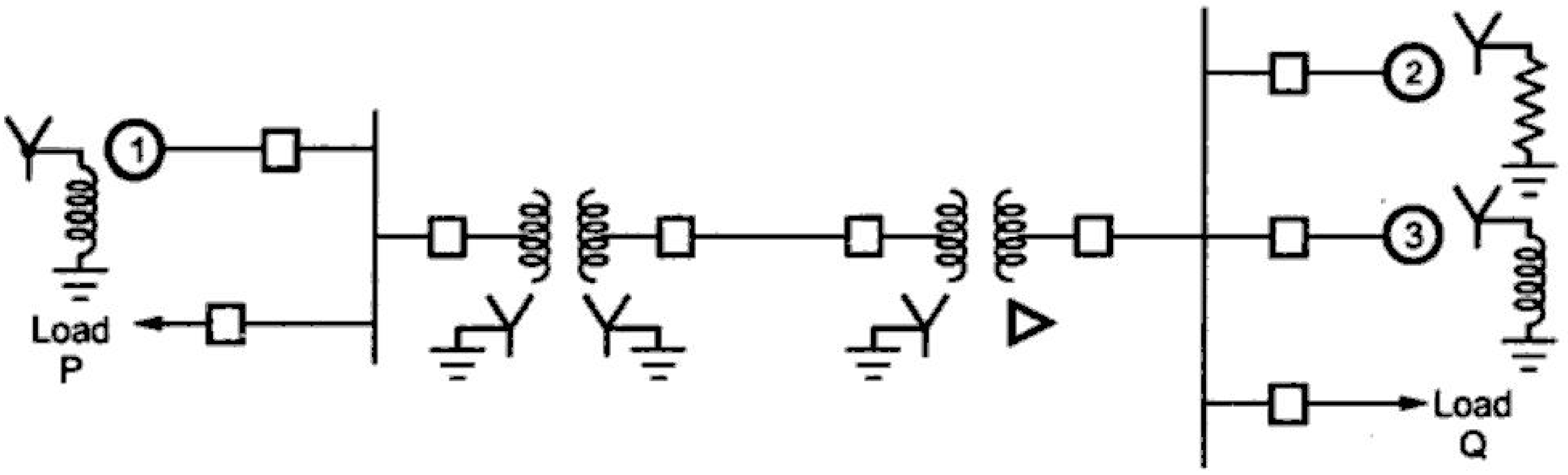


Fig. 1.4 Single line diagram

One generator grounded through reactor is connected to bus and through a transformer to the transmission line while two generators, one grounded through resistor and one grounded through reactor is connected to bus through a transformer to a transmission line at the other end. A load is connected on each of the bus. The ratings of the generators, transformers loads and reactances of different components of the circuit can also be represented on this diagram.

The only limitation of single line diagram is it cannot represent the conditions during unbalanced operation of a power system. Under the unbalanced operation of a power system, all three phases are to be shown for currents and voltages and single line diagram proves to be insufficient.

1.4 Elements of Power System

The power system is comprised of various elements such as generator, transformer, transmission lines, bus bars, circuit breakers, isolators etc. Now we will discuss in brief about these elements.

1.4.1 Generators

The generator or alternator is the important element of power system. It is of synchronous type and is driven by turbine thus converting mechanical energy into electrical energy. The two main parts of generator are stator and rotor. The stationary part is called **stator** or **armature** consisting of conductors embedded in the slots. The conductors carry current when load is applied on the generator. The rotating part or **rotor** is mounted on the shaft and rotates inside the stator. The winding on rotor is called **field winding.** The field winding is excited by d.c. current. This current produces high m.m.f. The armature conductors react with the m.m.f. produced by the field winding and e.m.f. gets induced in the armature winding. The armature conductors carry current when the load is connected to an alternator. This current produces its own m.m.f. This m.m.f. interacts with the m.m.f. produced by the field winding to generate an electromagnetic torque between stator and rotor.

The d.c. current required for field winding is supplied through exciter which is nothing but a generator mounted on the same shaft on which alternator is mount. The separate d.c. source may also be used sometimes to excite the field windings through brushes bearing on slip rings.

The generators are driven by prime mover which is normally a steam or hydraulic turbine. The electromagnetic torque developed in the generator while delivering power opposes the torque provided by the prime mover.

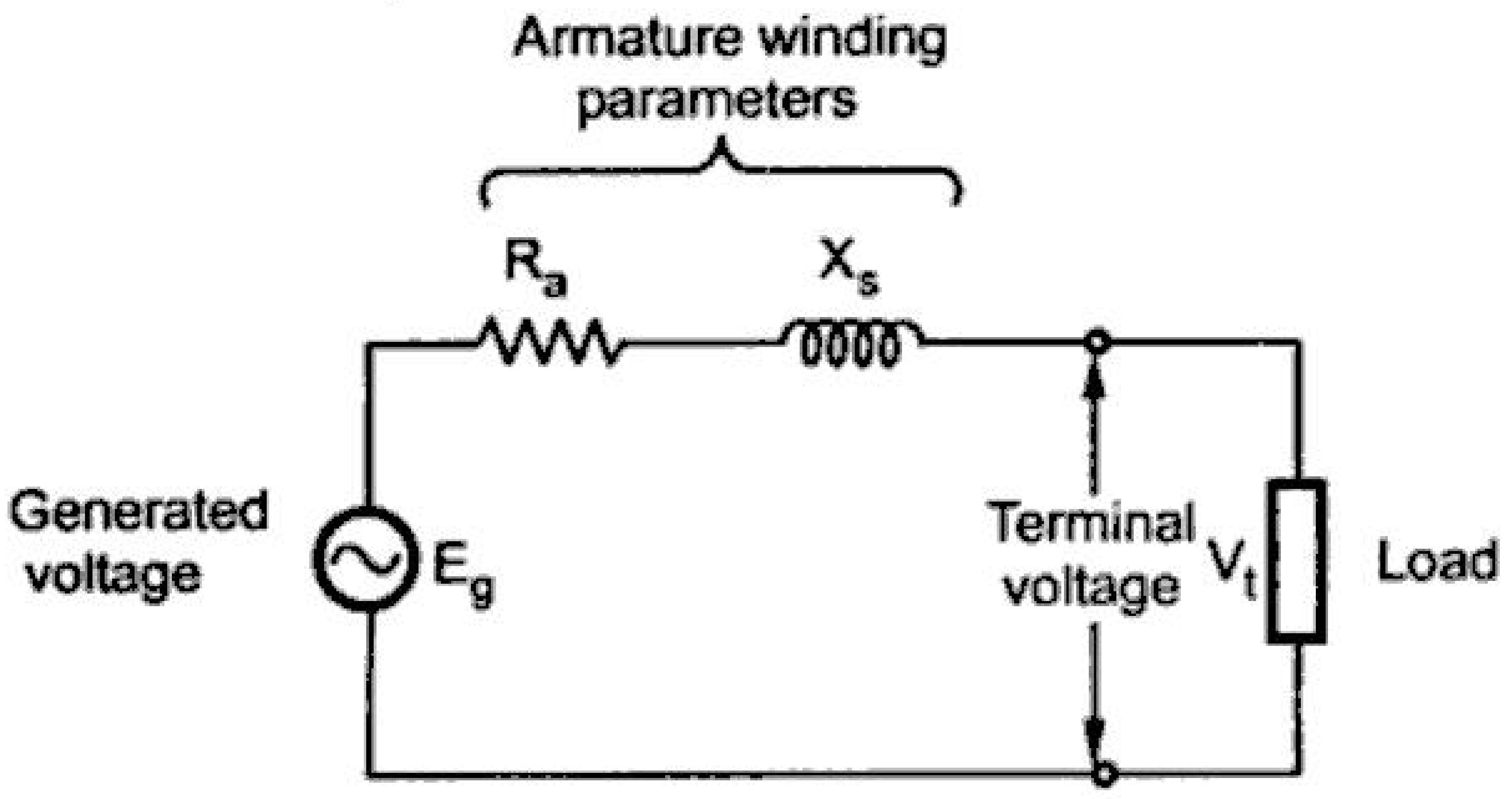


Fig. 1.5 Representation of alternator

With properly designed rotor and proper distribution of stator windings around the armature, it is possible to get pure sinusoidal voltage from the generator. This voltage is called no load generated voltage or generated voltage. The representation of generator is shown in the Fig. 1.5.

1.4.2 Transformers

For stepping up or down the system voltage, power transformers are used in the substations. At generating end, the voltage is only stepped up for transmission of power while at all the subsequent substations the voltage is gradually stepped down to reach finally to working voltage level.

Instead of using a bank of 3 single phase transformers, a single three phase transformer is used nowadays. The advantage of using this transformer is the easiness in its installation and only one three phase load tap changing mechanism can be used.

Generally naturally cooled, oil immersed, two winding, three phase transformers upto the rating of 10 MVA are installed upon lengths of rails fixed on concrete slabs having foundations 1 to 1.5 m deep. For more than 10 MVA ratings, forced oil, water cooling and air blast cooling type may be used. The tap changers are used for regulating the voltage of transformers.

1.4.3 Transmission Line

The transmission line forms the connecting link between the generating stations and the distribution systems. It carries the power generated by generating stations and makes it available for distribution through distribution network.

Any electrical transmission line has four major parameters which are important from the point view of its proper operation. These parameters are namely resistance, inductance, capacitance and conductance.

The resistance and inductance is uniformly distributed along the line. It forms series impedance. The resistance of a line is responsible for power loss. It is expected that the resistance of a line should be as low as possible so that the transmission system will be more efficient. Due to flux linkage, the conductor is associated with inductance which is distributed along the length of the line. For analysis, both resistance and inductance are assumed to be lumped.

The capacitance also exists between the conductors and is the charge on the conductors per unit of potential difference between them. The conductance between conductors or between conductors and the ground is due to leakage current at the insulators of overhead lines and through the insulation of cables. The leakage at conductors is negligible so the conductance between conductors of an overhead line is taken as zero. The conductance and capacitance between conductors of a single phase line or from conductor to neutral of a three phase line form the shunt admittance.

Depending upon the length of the transmission line it is classified as short transmission line, medium transmission line and long transmission line. For short line, its length is small so capacitance effects are small and are neglected.

1.4.4 Bus Bars

Bus bars are the common electrical component that connect electrically number of lines which are operating at the same voltage directly. These bars are of either copper or aluminium generally of rectangular cross-section. They can be of other shapes such as round tubes, round solid bars or square tubes.

The outdoor bus bars are of two types viz the rigid type or strain type.

In the rigid type of bus bars, pipes are used. The pipes are also used for making connections among different components. The pedestal insulators support the bus bars and the connections. The equipments and bus bars are spread out and it requires large space. The clearances remain constant as the bus bars are rigid.

It has following advantages.

1) The maintenance is easy as bus bars and connections are not very high from ground.
2) As pipe diameter is large, the corona loss is less.
3) Reliability is more than strain type.

Following are its limitations.

1) Larger area is required.
2) It requires comparatively high cost.

In strain type, bus bars are an overhead system of wires between two supporting structure and supported by strain type insulators. As per the size of the conductor, the stringing tension can be limited (500 - 900 kg).

The advantage of this type is its economy and it is recommended presently due to general shortage of aluminium pipes.

The material used in case of rigid type bus bars is aluminium pipes. The general sizes of pipes commonly used for voltages are as given below.

33 kV	40 mm
66 kV	65 mm
132 kV	80 mm
220 kV	80 mm
400 kV	100 mm

Due to rapid oxidization of aluminium, proper care must be taken while doing connections. In order to avoid strain of supporting insulators due to thermal expansion or contraction of pipe, joints should be provided.

In case of strain type arrangement, material used is ACSR (Aluminium Conductors with Steel Reinforcement) and all aluminium conductors. For high ratings of bus bars bundled conductors are used. The commonly used sizes are as below.

66 kV	37/2.79 mm	ACSR
132 kV	37/4.27 mm	ACSR
220 kV	61/3.99 mm	ACSR
400 kV	61/4.27 mm	ACSR in duplex

1.4.5 Circuit Breaker

The circuit breakers are used to open or close a circuit under normal and faulty conditions. It can be designed in such a way that it can be manually operated or by remote control under normal conditions and automatically operated during fault. For automatic operation, relay circuit is used.

The circuit breakers are essential as isolators cannot be used to open a circuit under normal conditions as it has no provision to quench arc that is produced after opening the line. It has to perform following functions.

i) Full load current is to be carried continuously.

ii) Opening and closing the circuit on no load.

iii) Making and breaking the normal operating current.

iv) Making and breaking the fault currents of magnitude upto which it is designed for.

Upto 66 kV voltages, bulk oil circuit breakers are used. Voltages greater than 66 kV, low oil circuit breakers are used. For still high voltages, air blast, vacuum or SF_6 circuit breakers are used.

1.4.6 Isolators

In order to disconnect a part of the power system for maintenance and repair purposes, isolating switches are used. These are operated after switching off the load by means of a circuit breaker. The isolators are connected on both sides of circuit breakers. Thus to open isolators, circuit breakers are to be opened first.

An isolator is essentially a knife switch and is designed to open a circuit under no load that is lines in which they are connected should not be carrying any current.

Use of isolators in a substation is shown in the Fig. 1.6.

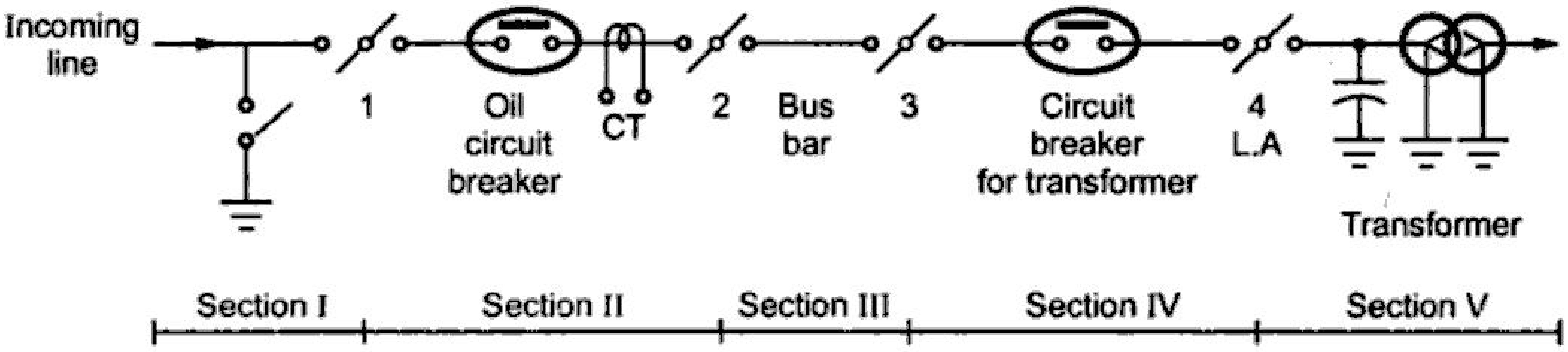


Fig. 1.6 Line diagram of substation with use of isolating switches

As shown in the Fig. 1.6, there are 5 sections. With the help of isolators, each section can be disconnected for repair and maintenance. If it is required to do maintenance in section 4, then the circuit breaker in that section is to be opened first and then open the isolators 3 and 4. Thus section 4 is open for maintenance. After maintenance, the isolators 3 and 4 are to be closed first and then circuit breaker is closed.

In some cases, isolators are used as circuit breaking devices. But it is limited by particular conditions such as power rating of given circuit. The isolators are of two types viz single pole and three pole isolators.

1.5 Sources of Electric Energy

The various energy sources are classified into two main groups.

a) Non-conventional or renewable energy sources.

b) Conventional or non-renewable energy sources.

1.5.1 Non-conventional or Renewable Energy Sources

These energy sources are available abundantly in nature and can be reused again.

The various non-conventional energy sources are as follows.

i) Solar energy
ii) Wind energy
iii) Hydraulic energy
iv) Tidal energy
v) Wave energy
vi) Geothermal energy
vii) Ocean thermal energy
viii) Biogas energy
ix) Biomass energy
x) Fuel cells

1.5.1.1 Advantages of Non-conventional Energy Sources

The leading advantages of non-conventional energy sources are

1) They are abundantly available in nature.
2) They do not pollute the atmosphere.
3) They are available in large quantities.
4) They are well suited for decentralized use.
5) The plants using these sources have very less (theoretically no) maintenance cost.

1.5.1.2 Disadvantages of Non-conventional Energy Sources

The disadvantages of non-conventional energy sources are

1) They are available at very low intensities.
2) These sources are available in nature during particular periods which is uncertain.
3) Less efficiency of the power plants.
4) High initial cost.

1.5.2 Conventional or Non-renewable Energy Sources

These are the energy sources which once used cannot be recovered any more. They are depleting in nature.

The various non-renewable energy sources are

i) Thermal energy from a) Coal coke b) Petroleum products like petrol, Diesel, Kerosene etc. c) Natural gas.

ii) Nuclear energy.

1.5.2.1 Advantages of Conventional Energy Sources

Following are the advantages of conventional energy sources.

1) Their efficiency is more.

2) Their initial cost is comparatively less.

3) Their intensities are high.

1.5.2.2 Disadvantages of Conventional Energy Sources

The disadvantages of conventional energy sources are

1) Their running and maintenance cost is high.

2) They are depleting in nature.

3) They cause pollution to atmosphere by different means.

Comparison between renewable and non-renewable energy sources

Sr. No	Renewable energy sources	Non-renewable energy sources
1.	They don't cause pollution to atmosphere.	They cause pollution to atmosphere.
2.	Their efficiency is comparatively less.	Their efficiency is comparatively high.
3.	They are available at low intensities.	They are available at high intensities.
4.	Their initial cost is comparatively less.	Their initial cost is comparatively high.
5.	Their running cost is less.	Their running cost is more.

.6 Electrical Equipments used in Power Station

A power station generates an electrical energy by using one of the energy sources. modern power station contains number of electrical equipments. The important electrical quipments are,

. **Alternator :** This is most important equipment. It is always coupled to the turbine, hichever type of the station it may be i.e. steam, gas, nuclear etc. The turbine acts as a rime mover of alternator. The alternator converts the mechanical energy received from e turbine into an electrical energy.

Alternators are generally hydrogen cooled or air cooled. The necessary excitation to the alternators is provided by the main and pilot exciters directly connected to the alternator shaft.

2. Transformer : This is another important electrical equipment which is used to raise or lower the available voltage levels as per the requirement. In a power station, different types of transformers are used, which are :

i) Main step up transformer which steps up the generated voltage for the further transmission.

ii) Station transformer which is used for the general service in the power station itself.

iii) Auxiliary transformers which supply to individual auxiliary unit.

3. Switchgear : This includes such a equipment which locates the fault on the power system and isolates the faulty part from the system. It contains circuit breakers, relays, isolating switches, fuses and other controlling devices.

Alternator gives its output to the bus bar through the transformer and proper switchgear equipments.

1.7 Steam Power Station

A generating station which converts the heat energy of coal combustion into an electrical energy is called **steam** or **thermal** power station.

In this power station, the steam is produced in the boiler by using the heat of the coal combustion. The steam is then expanded in steam turbine which drives the alternator which converts the mechanical energy of the turbine into an electrical energy. The exhaust steam gets condensed in the condenser and fed back into the boiler again, completing the cycle of the power station. This principle is called Rankine cycle.

The energy conversion involved in steam power station is shown in the Fig. 1.7.

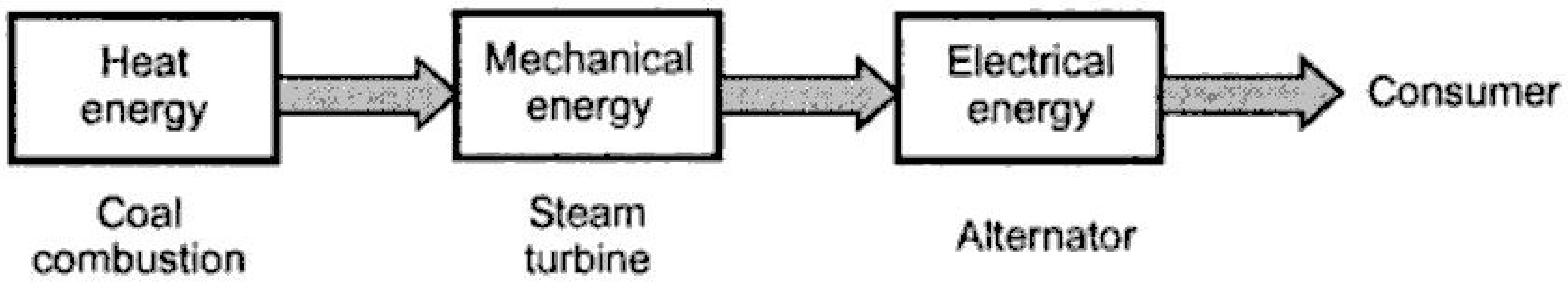


Fig. 1.7 Energy conversion

1.7.1 Factors for Selection of Site

The following factors are to be considered for the selection of site for the steam power station, in order to achieve the economical and successful operation of the plant.

1. Supply of fuel : The main fuel for the steam power plant is coal. Thus the power station should be located near the coal mine so that fuel supply is continuous and adequate. If the plant is located away from the coal mine then sufficient transportation facility must be available.

2. Availability of water : For the condenser, huge amount of water is required. Hence site must be near the river so that abundant quantity of cooling water is available.

3. Transportation facilities : For transporting the equipments and the machinery required by a modern steam power plant, the site selected must be easily accessible by rail and road.

4. Cost and type of land : The land must be available at a reasonable price to keep the initial cost low. There must be provision for the extension of the plant. The type of the land must be such that it should be able to withstand the weight of the heavy equipments to be installed.

5. Distance from load centers : To keep the cost of the transmission and transmission losses to minimum, the site must be nearer to the load centers. For d.c. system, transmission loss plays an important role but a.c. power can be transmitted at high voltages with reduced transmission cost. Thus this factor is more important for d.c. supply system.

6. Distance from populated area : The continuous burning of coal at the power station produces smoke, fumes and ash, which pollutes the surrounding area. Such a pollution due to smoke is dangerous for the people living around. Hence the site of the plant must be at a considerable distance from the populated area.

All these factors affect the selection of site for the steam power station.

1.7.2 General Arrangement of Steam Power Plant

Though steam power plant simply involves the conversion of heat energy to the mechanical energy, it requires many types of supporting arrangements. The Fig. 1.8 shows the schematic arrangement of steam power station. (See Fig. 1.8 on next page)

The coal is burnt in a place called grate in a boiler. The flue gases are evolved which heats the water in a boiler. The water is converted to a steam by absorbing heat from the flue gases. This steam is called wet steam as it contains suspended water particles. This steam is passed to the superheater where it is converted to superheated steam from the wet steam. This superheated steam is then expanded in the turbine which rotates the turbine. Thus the heat energy is converted to a mechanical energy. The turbine shaft is coupled to an alternator which converts the mechanical energy into an electrical energy. This is then given to the bus bar through a transformer and proper switchgear arrangement.

After expanding in the turbine, the exhaust steam is passed through the condenser. In the condenser, the steam is converted into liquid called condensate. Using the condensate extraction pump, the condensate is taken to economizer. The economizer again transfers the heat from flue gases to the condensate and then transfers the heated water to the boiler. Thus the cycle is completed. The exhaust flue gases are released to the atmosphere through the chimney.

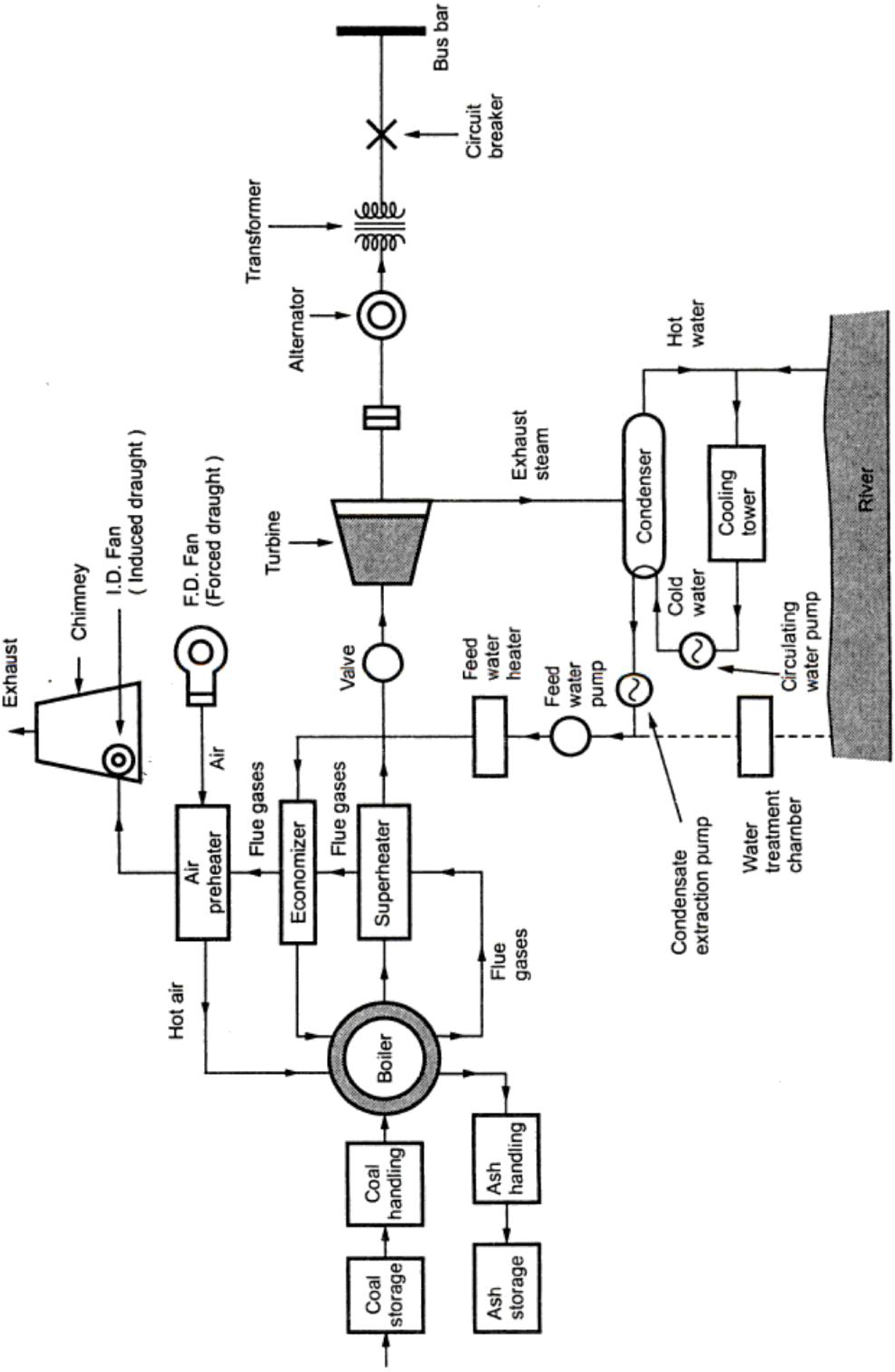


Fig. 1.8 Schematic arrangement of steam power station

1.7.3 Constituents of Steam Power Station

The various constituents of steam power station can be divided into the following stages for the ease of understanding the working of the power plant.

1. Fuel and ash circuit
2. Steam generating circuit
3. Steam turbine
4. Alternator
5. Feed water circuit
6. Cooling water circuit

1.7.3.1 Fuel and Ash Circuit

In steam power plant, the coal is used as a fuel. The coal is stored in a coal storage plant where coal is transferred from all the parts of the country by the rail or the road. The storage helps to supply the coal continuously, in case of situations like strikes, failure of transportation system etc. Then the coal is transferred to the coal handling plant where the coal is pulverized i.e. crushed into small pieces. The pulverization increases the surface exposure of the coal and this helps for rapid combustion of coal without using large quantity of air. Such a crushed coal is transferred to the boiler from the coal handling plant.

As a result of combustion of the coal, large quantity of ash is produced in the boiler. For the proper combustion of the coal, ash is removed to the ash handling plant. Then it is delivered to the ash storage plant, from where it is disposed off.

1.7.3.2 Steam Generating Circuit

The main component of steam generating circuit is the boiler. But many other auxiliary equipments are used so as to completely utilize the heat of flue gases.

1. Boiler : The boiler is a closed vessel where water is converted to the steam using the heat of the coal combustion. Hence the boiler is called **steam generator.** In the boilers, the grate is provided for the combustion of coal. The steam produced in the boiler contains suspended water particles and hence called wet steam.

2. Superheater : It is an accessory attached to the boiler and located in the path of flue gases leaving the boiler and flowing towards chimney. By using the heat of the flue gases, the superheater converts the wet steam into superheated dry steam. There are two advantages of superheating that it increases the overall efficiency and it avoids the corrosion of the turbine blades due to wet steam. The superheated steam is then passed to the turbine through a main valve between the two. The two types of superheaters used are radiant type and convection type.

3. Economizer : It is another accessory attached to the boiler and located in the path of flue gases. Thus it utilizes the heat of flue gases which would otherwise wasted to the atmosphere. The water from the feed pump is passed through the economizer to the boiler drum so that before entering the boiler, it is heated and hence less efforts are required to convert it into steam. This increases the overall boiler efficiency, saves the fuel and reduces the stress on the boiler.

4. Air preheater : This is also an accessory attached to the boiler and located in the path of flue gases. The air is required for the coal combustion. Air is drawn from the atmosphere by a forced draught fan and is supplied to the air preheater. The air preheater extracts the heat from the flue gases and makes the air hot before supplying to the boiler. This increases the temperature of the furnace and helps in the production of the steam. This increases the thermal efficiency and the steam capacity per square metre of the boiler surface.

The two types of air preheaters used are recuperative type and the other is regenerative type.

1.7.3.3 Steam Turbine

The dry and superheated steam from the superheater is supplied to the turbine. The heat energy of the steam is converted to the mechanical energy as steam passes over the turbine blades. There are two types of steam prime movers available, steam engine and steam turbine. The steam turbine is practically used because of the following advantages.

i) High efficiency ii) Simple construction iii) Low maintenance

iv) High speed v) Less floor area vi) No flywheel required

vii) Less problems of vibrations

The steam turbines are classified into two types as impulse turbine and reaction turbine.

In the **impulse turbine**, the steam expands completely in the nozzle and pressure over the moving blades remaining constant. While doing so, the steam attains very high velocity and impacts on moving blades giving rise to an impulsive force on them. Thus the turbine starts rotating.

In the **reaction turbine,** steam is partially expanded in the stationary nozzle and remaining expansion takes place on the moving blades. This causes reaction force on the moving blades and the turbine stats rotating.

The commercial turbines nowadays use series combination of impulse and reaction turbines, due to which steam can be used more efficiently.

1.7.3.4 Alternator

The alternator shaft is coupled to the turbine. When the turbine shaft rotates, the alternator shaft rotates and it converts the mechanical energy into an electrical energy. The electrical energy from the alternator is given to the bus bar through transformer, circuit breakers and isolators.

1.7.3.5 Feed Water Circuit

The condensate leaving the condenser is used as the feed water. Because it goes to the boiler, it is first heated in a closed feed water heater. Then it is passed to economizer where it is further heated and then passed to the boiler. This increases the overall efficiency of the plant.

The feed water source is generally river or a canal. It contains suspended and dissolved impurities. The boiler needs clean and soft water for longer life and better efficiency. Hence the feed water is purified. It is stored in the tanks and by the different actions like sedimentation, filtration etc., it is made soft and pure. Such a pure feed water is used for the steam generation in the boiler.

1.7.3.6 Cooling Water Circuit

For improving the plant efficiency, the expanded steam coming out of the turbine, passes through the condenser where it is condensed into water. The condenser is very important as it creates a very low pressure at the exhaust of the turbine thus helps in the expansion of steam in the turbine at low pressure.

For condensation of steam, a flow of natural cold water is circulated through the condenser. This takes the heat from the exhaust steam and gets heated. This hot water is discharged at a suitable location or is passed through a cooling tower so that it is again converted to cold water. Then it is recirculated through the condenser by a pump. The condensed steam can be used as a feed water to the boiler.

The two types of condensers used are jet condenser and surface condenser.

1.7.4 Advantages

1. The fuel used is a coal, which is cheap.
2. The initial cost is less compared to other power stations.
3. It requires less floor space area compared to hydro-electric power station.
4. The fuel is easily available.
5. The fuel can be easily transported to the site hence site can be anywhere and not always near the coal mines.
6. The cost of the generation is less than the diesel.

1.7.5 Disadvantages

1. Due to the smoke and fume, pollutes the surrounding atmosphere.
2. Running cost is higher than hydro-electric power plant.

1.7.6 Efficiency

For a steam power station, two efficiencies are defined which are thermal efficiency and the overall efficiency.

Thermal efficiency is the ratio of heat equivalent of the mechanical energy transmitted to the turbine shaft to the heat of the combustion of coal.

$$\boxed{\eta_{\text{thermal}} = \frac{\begin{bmatrix}\text{Heat equivalent of mechanical energy} \\ \text{transmitted to turbine}\end{bmatrix}}{\text{Heat of coal combustion}}}$$

The **overall efficiency** is the ratio of heat equivalent of electrical output from alternator to the heat of coal combustion. The overall efficiency of steam power station is very low about 20 to 25 %.

$$\boxed{\eta_{\text{overall}} = \frac{\text{Heat equivalent of electrical output}}{\text{Heat of combustion of coal}}}$$

The overall efficiency depends on number of factors and hence can be expressed as,

$$\boxed{\eta_{\text{overall}} = \eta_{\text{thermal}} \times \eta_{\text{electrical}} \times \eta_{\text{boiler}}}$$

where,

$\eta_{\text{electrical}}$ = Electrical efficiency of an alternator which is practically high, above 90 %.

η_{boiler} = Boiler efficiency considering the effect of economizer and air preheater, which is about 85 %.

1.8 Hydro-electric Power Station

A power generating station which uses the potential or kinetic energy of water for th generation of an electrical energy is called **hydro-electric power station.**

Water has a kinetic energy when it is in motion. While the water stored at high leve has a potential energy. The difference in level of water between the two points is calle **head.** Such a water head is practically created by constructing reservoirs across river o lake. Generally a dam is constructed at high altitudes, which can be used as a continuou source of the water for the hydro-electric power stations. The water from the dam is take through pipes and canals to the water turbine, which is at lower level. The turbine obtain the energy from the falling water and changes it into a mechanical energy. This mechanica energy of the turbine is then used to drive the alternator, which converts the mechanica energy into an electrical energy. The energy conversion involved in hydro-electric powe generation is shown in the Fig. 1.9.

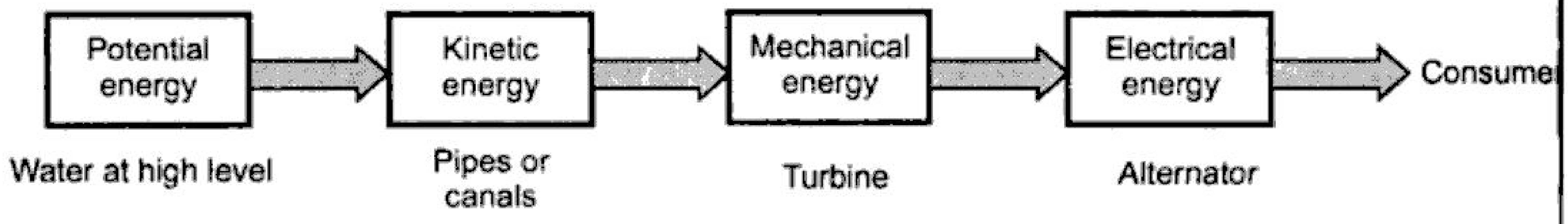


Fig. 1.9 Energy conversion

1.8.1 Factors for Selection of Site

The water reservoir like dam cannot be constructed anywhere. There are number of factors affecting the choice of site for the hydroelectric power station.

1. Availability of water : As the basic requirement of hydro-electric plant is the water, the availability of huge quantity of water is the main consideration. The plant must be constructed where sufficient quantity of water is available at a good head. The previous rainfall records are studied and the maximum and minimum quantity of water available during the year is estimated. Considering the losses such as evaporation, the water necessary for the plant is calculated. Then by comparing both the estimations, the choice of the site is done.

2. Storage of water : The rainfall is not consistent every year. Hence the available water should be stored. This makes necessary to construct dams. The storage helps in equalizing the flow of water throughout the year. So site should provide sufficient facilities for erecting dam and the storage of water.

3. Head of water : For getting sufficient head, the dam or reservoir should be constructed at a height in a hilly area. The availability of the head directly affects the cost and economy of the power generation. So site should be selected in proper geographical area, which can give sufficient water head.

4. Cost and type of land : The initial cost of the project includes the cost of the land. Hence land must be available at a reasonable price. Similarly the type of the land must be such that it should able to withstand the weight of the heavy equipments to be installed.

5. Transportation facilities : For transporting the equipments and the machinery, the site selected must be easily accessible by rail and road.

6. Distance from load centers : The load center is connected to the site by the transmission lines. Hence to keep the cost of the transmission lines minimum and the losses occurring in the line minimum, the distance of the site from the load centers must be less. Otherwise the overall cost increases considerably.

All these factors affect the selection of site for the hydro-electric power station.

1.8.2 General Arrangement of Hydro-electric Plant

Though hydro-electric power station simply involves the conversion of hydraulic energy to the mechanical energy, it requires many types of supporting arrangements. The Fig. 1.10 shows the schematic arrangement of hydro-electric power station which uses water supply from an artificially constructed dam.

The dam is constructed across the river and water from catchment area is collected behind the wall of the dam, in high mountains. A pressure channel is taken from such a water reservoir which takes water to a surge tank. The surge tank is a controlling room which controls the flow of water i.e. adjusts the discharge of water according to the need of the turbine and load on it. Trash rack does not allow floating and other impurities to

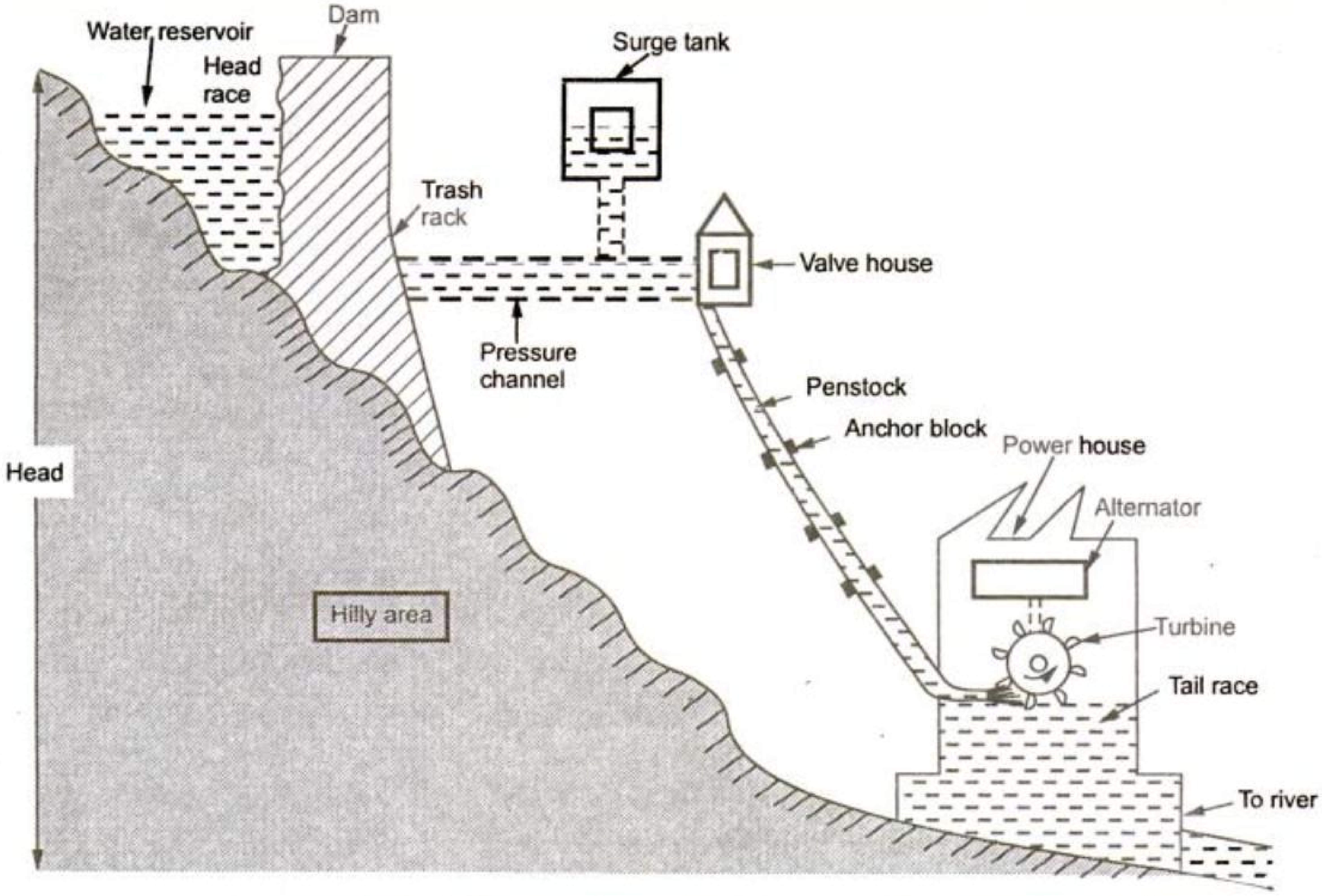


Fig. 1.10 Schematic arrangement of hydro-electric power plant

pass to the turbine. The pressure channel plays a very important role. It relieves the pressure on the penstocks when the turbine valves are open or closed suddenly. The water is then taken to a valve house from where the penstocks start. The valve house contains main sluice valve and the automatic isolating valves. These valves also regulate the flow of water to the power house and isolates the supply of water if there is any emergency such as bursting of a penstock. Through the penstocks, the water is taken to the power house which consists of turbine and the alternator. The penstocks are nothing but the steel pipes which are arranged in the form of open or closed conduits, supported by the anchor blocks.

When the water from the penstock is hammered through a nozzle, on the turbine blades, the turbine starts rotating. At this stage the hydraulic energy is converted to a mechanical energy. The turbine drives the alternator which is coupled to the shaft of the turbine. The alternator converts the mechanical energy into an electrical energy. This electrical energy is then transmitted to the load centers. The water collected from the turbine is called tail race. This tail race is then taken off to the river.

1.8.3 Constituents of Hydro-electric Power Station

Let us discuss the constituents and their functions in the operation of the hydro-electric power station.

1.8.3.1 Dam

The water reservoir in the form of a dam is the main part of the power station. It stores the water, provides the continuous supply of water and maintains the necessary water head. The dams are built up of stones and concrete. The design and type of the dam is selected according to the topography of the site and economical aspects.

1.8.3.2 Spillways

There are certain times when the river flow exceeds the storage capacity of the dam, due to the heavy rainfall. The spillways are provided to discharge this surplus water and maintain safe water level in the dam.

1.8.3.3 Surge Tank

This is an important projecting device in a hydro-electric power plant. It is built just before the valve house. It protects the penstocks from bursting due to the sudden pressure changes.

If the load on the turbine is thrown off suddenly then by the governing action, the turbine input gates get suddenly closed. Thus there is sudden stopping of water at the lower end of the penstock. This time the excess water at the lower end of the penstock, rushes back to the surge tank. The surge tank water level increases. Thus the penstock is protected from bursting due to high pressure. The surge tank absorbs this high pressure swing by increasing its water level.

On the other hand, when the load on the turbine suddenly increases, the additional water required is drawn from the surge tank. This satisfies the increased water demand instantly.

Thus the surge tank controls the pressure changes created due to rapid changes in the water flow in penstock and hence protects the penstock from water hammer effects which might burst the penstock.

1.8.3.4 Penstocks

The penstocks are made up of steel or concrete and arranged in the form of conduits, supported by the anchor blocks. The penstocks are used to carry water to the turbine. For the low head (less than 30 m) power stations, the concrete penstocks are used. The steel penstocks are suitable for any head.

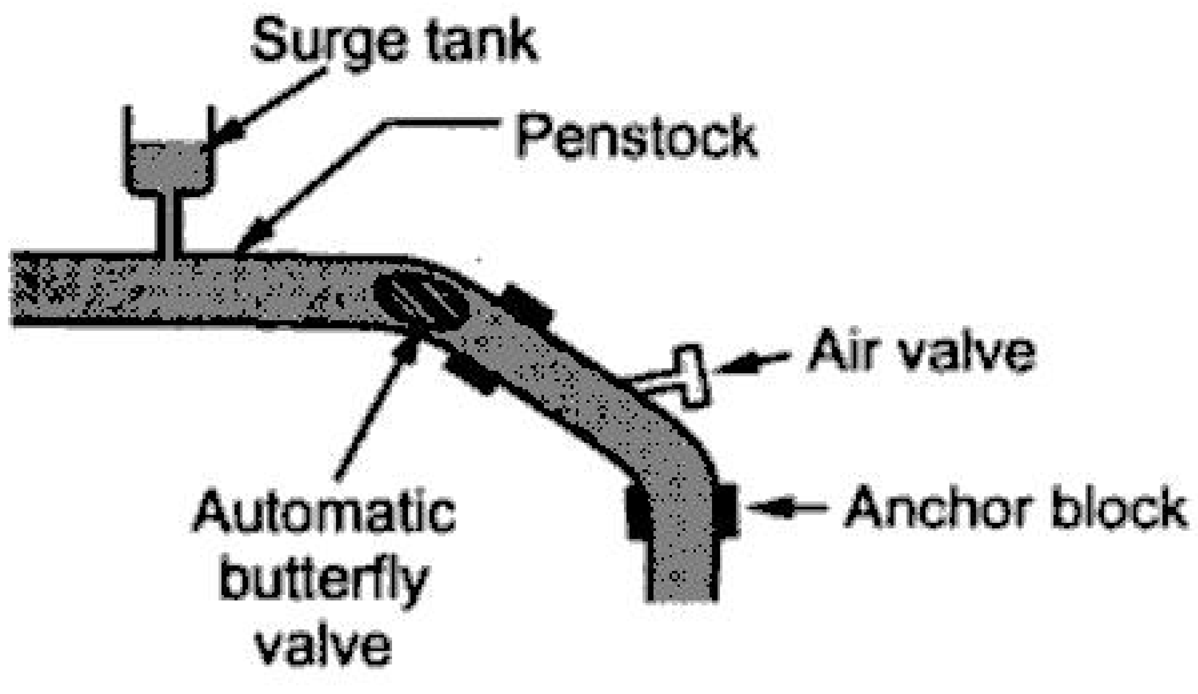


Fig. 1.11 Protecting devices of penstock

There are certain protective devices attached to the penstocks. These devices are shown in the Fig. 1.11.

The automatic butterfly valve completely shuts off the water flow if the penstock bursts.

The air valve maintains the air pressure inside the penstock equal to the outside atmospheric pressure.

The anchor block supports the penstock and holds it in the proper position.

The surge tank also protects the penstock from sudden pressure changes.

1.8.3.5 Water Turbines

The main two types of water turbines are,

i) Impulse and ii) Reaction

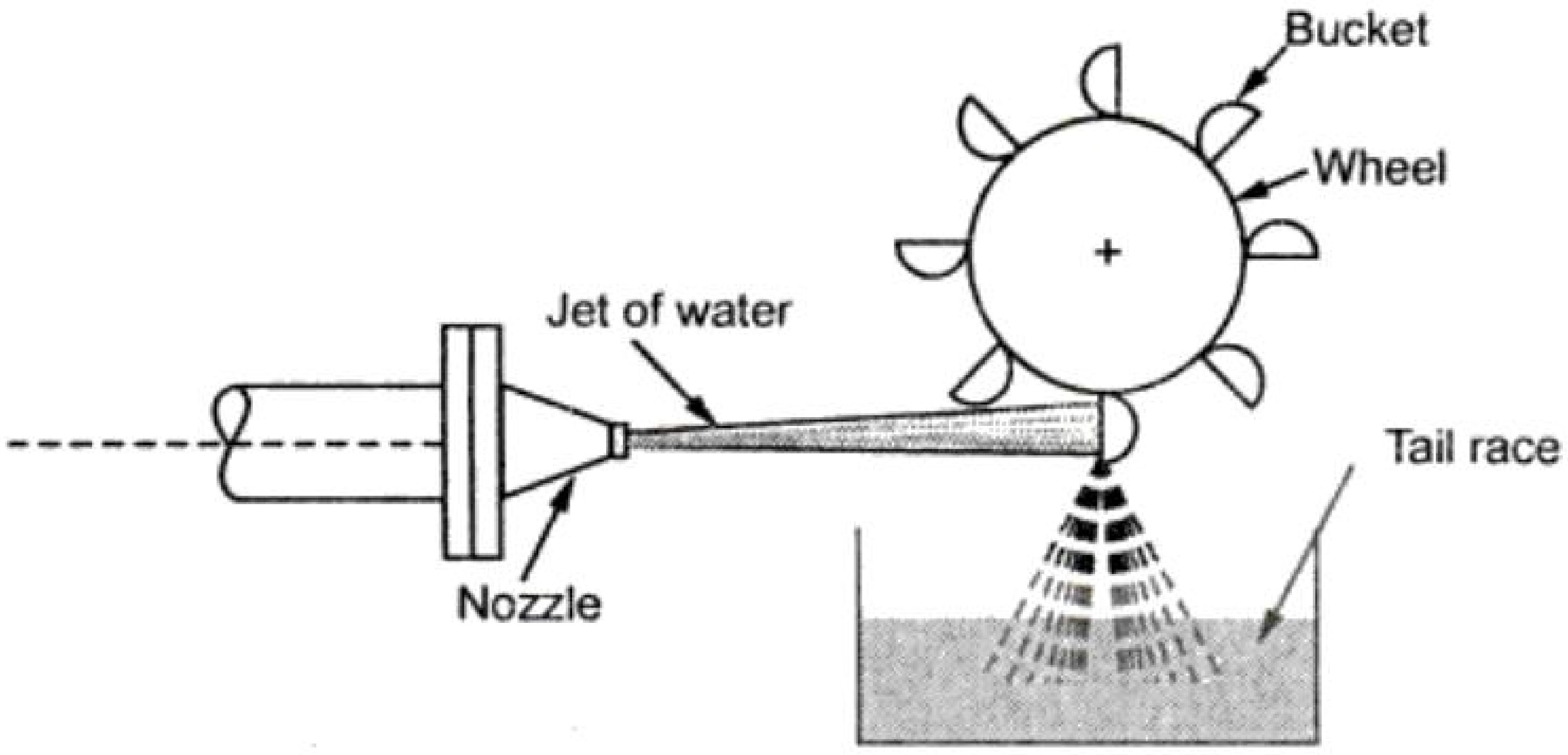


Fig. 1.12 Impulse turbine

In an impulse turbine, the entire pressure of water is converted into a kinetic energy in a nozzle. Then the water jet is forced on the turbine with a large velocity which drives the wheel. The pelton wheel is an example of impulse turbine which is shown in the Fig. 1.12.

It contains elliptical buckets mounted on the periphery of a wheel. The force of water jet on the buckets, drives the wheel and the turbine. There is a needle or spear at the tip of the nozzel. The governor controls the needle which controls the force of the jet, according to the load demand. The impulse turbines are used for the high head power stations.

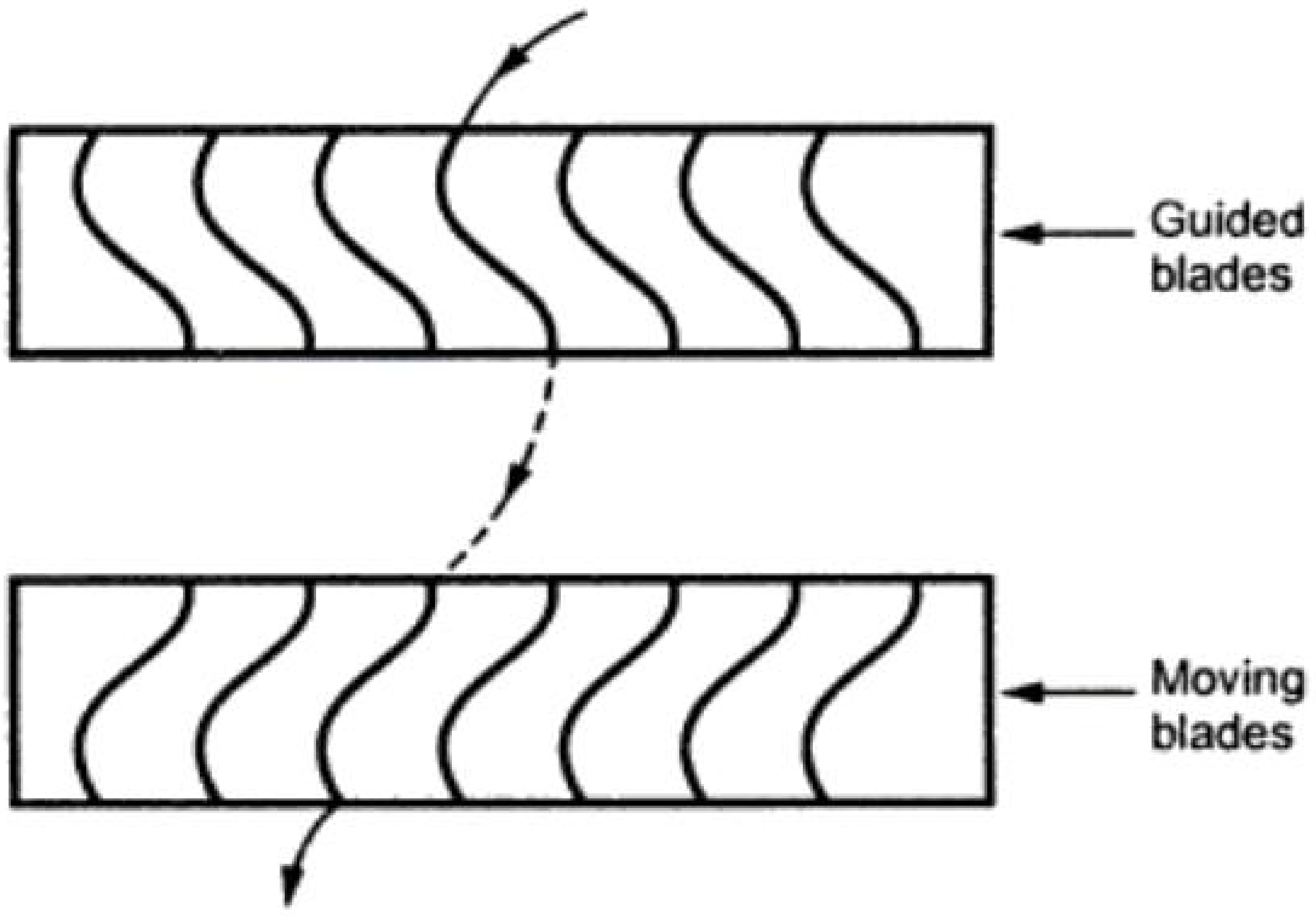


Fig. 1.13 Reaction turbine

In the reaction turbines, the water enters the runner, partly with pressure and partly with velocity head. There are two types of reaction turbines.

i) Francis and ii) Kalpan

The Fig. 1.13 shows the basic principle of reaction turbine. The reaction turbine consists of an outer ring of stationary guided blades and an inner ring of rotating blades. The guided blades control the flow of water to the turbine. Water flows radially inwards and changes to a downward direction when it passes through the rotating blades. While passing over the rotating blades, the pressure and velocity of water are decreased. This causes reaction force to exist which drives the turbine. For large variation of head, Kalpan is used as its efficiency does not vary with change in load. For fairly constant head, a Francis or Propeller turbine is used.

The reaction turbines are used for the low head power stations.

1.8.4 Advantages

1. If the proper site is selected, the continuous water supply is available.
2. Requires no fuel as water is used.
3. No burning of fuel hence neat and clean site as no smoke or ash is produced.
4. It does not pollute the atmosphere.
5. The operating cost is very low as free water supply is available.
6. The turbines in these plants can be switched on and off in a very short period of time.
7. It is relatively simple in construction, self contained in operation and requires less maintenance.
8. It is robust and has very long life.
9. It gives high efficiency over a considerable range of load. This improves the overall system efficiency.
10. It provides the additional benefits like irrigation, food control, afforestation etc.
11. Being simple in design and operation, highly skilled workers are not necessary for the daily operation. Thus man power requirement is low.

.8.5 Disadvantages

1. Due to the construction of dam, very high capital cost.
2. The low rate of return.
3. Uncertainity of availability of water due to unpredictable rainfall.
4. As its location is in hilly areas and mountains, the long transmission lines are necessary for the transmission of generated electrical energy. This requires high cost.
5. The large power stations disturb the ecology of the area by the way of disforestation, destroying vegetation and uprooting people.
6. Highly skilled and experienced persons are necessary at the time of construction.

.9 Nuclear Power Station

A generating station which converts the nuclear energy into an electrical energy is lled **nuclear power station.**

In such a power station, heavy radioactive elements like Uranium (U^{235}), Thorium h^{232}), are subjected to the nuclear fission. The fission is breaking of nucleus of heavy om into the parts by bombarding neutrons. This is carried out in a special nuclear actor. During the nuclear fission, huge amount of energy is released.

The heat energy thus released is used in raising the steam at high pressure and temperature. The steam turbines are operated using the high temperature steam. The turbines converts the heat energy into a mechanical energy. The turbine drives the alternator which converts mechanical energy into an electrical energy.

The energy conversion involved in the nuclear power station is shown in the Fig. 1.14.

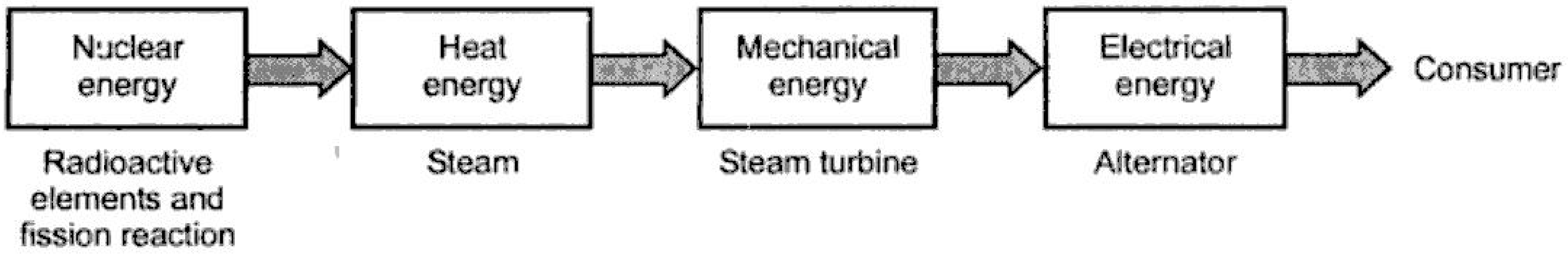


Fig. 1.14 Energy conversion

1.9.1 Conversion of Nuclear Energy

According to Einstein's hypothesis, the relation between the energy released by the nuclear reaction of the mass is given by,

$$\boxed{E = mc^2}$$

where E = Energy released in joules

m = Actual mass converted into energy in kg

c = Velocity of light = 3×10^8 m / s

There are three types of nuclear reactions, radioactive decay, fission and fusion. Out of this, only fission is used to produce the energy.

The fission reaction is achieved by bombarding an electrically neutral neutron, on the positively charged nucleus of radioactive element. This results in the sustained reaction to release two or three neutrons for each one absorbed in fission.

The immediate products of fission reactions such as xenon (Xe^{140}) and strontium (Sr^{94}) are fission fragments and are the decay products. The complete fission of 1 gm of U^{235} nucleus produces 0.948 MW energy per day.

1.9.2 Factors for Selection of Site

The following factors are to be considered for the selection of site for the nuclear power station.

1. Availability of water : Water is a secondary working fluid and used as a coolant for the cooling purpose, in the nuclear power station. A huge amount of water is necessary for this purpose. Hence site must be near the river or canal so that abundant quantity of cooling water is available.

2. Disposal of waste : The immediate products of fission reaction are the waste products which are radioactive in nature. These can cause problems to the health of the people and hence must be disposed quickly. Such a waste is either burried in deep pits or disposed off in the sea. Hence the site should be selected so that their is sufficient arrangement for disposal of such radioactive waste products.

3. Distance from populated area : The radioactive elements are hazardous to the health of the people around. There is always danger of presence of radioactivity in the atmosphere near the plant. Hence as a safety measure the site itself must selected to far away from the populated area. Practically a dome is used in the plant, which restricts radioactivity to spread in the atmosphere.

4. Transportation facilities : For transporting the equipments and the machinery required, there must be adequate transportation facilities. The site must accessible by a rail or road so that it is easy for the movement of the workers, working in the plant.

5. Nearness to the load centres : Though the site should be away from the populated area near the river or sea, it should not be too large distance, due to which transmission cost may increase tremendously.

6. Cost and type of land : The land price must be reasonable and the bearing capacity of the land should be good enough to withstand the forces due to heavy equipments of the plant.

All these factors affect the selection of site for the nuclear power station.

1.9.3 General Arrangement of Nuclear Power Plant

The Fig. 1.15 shows the schematic arrangement of a nuclear power plant.

The entire arrangement can be divided into following stages.

1. Nuclear reactor
2. Heat exchanger (Steam generator)
3. Steam turbine
4. Alternator
5. Cooling water circuit.

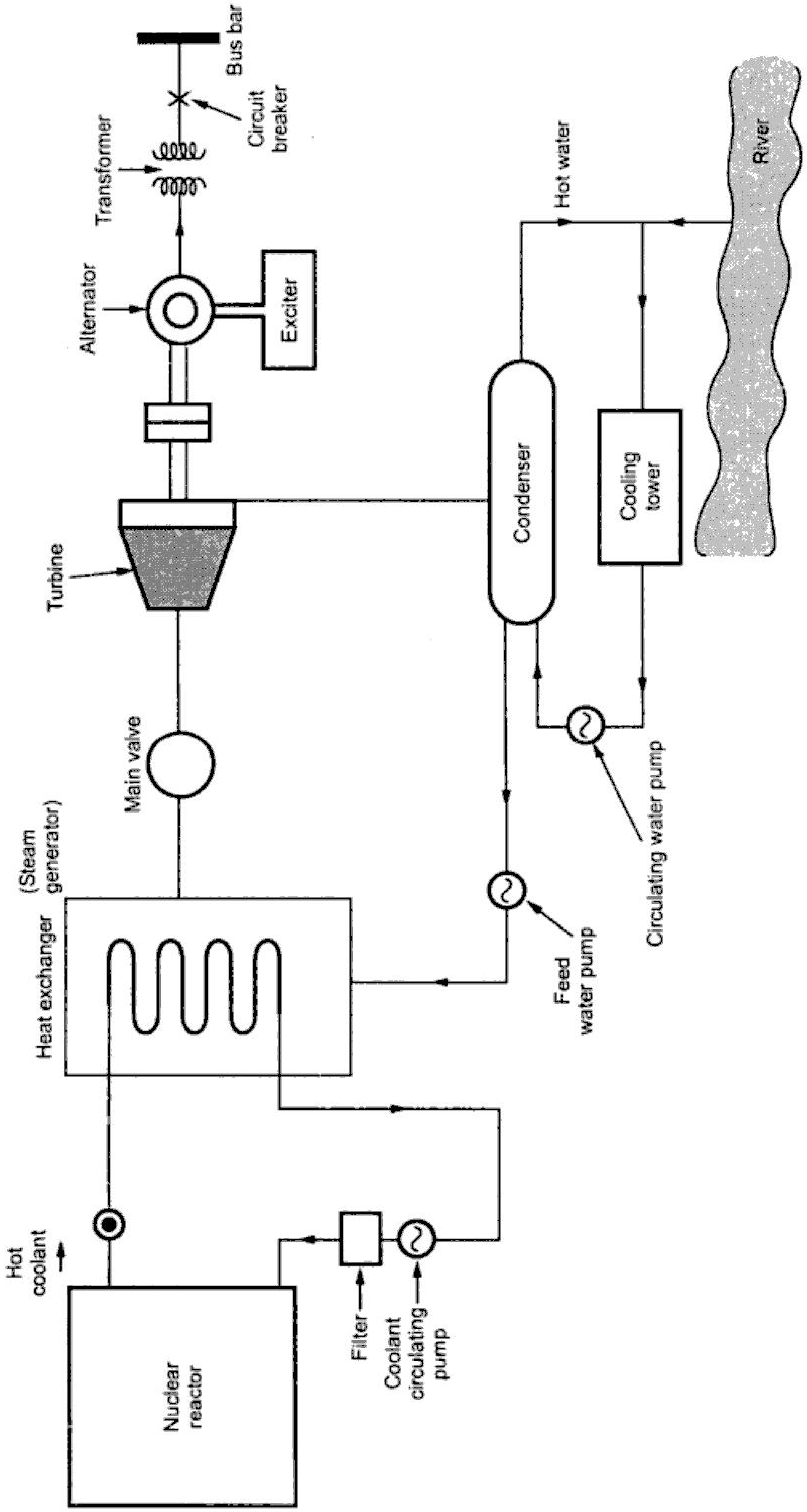


Fig. 1.15 Schematic arrangement of nuclear power station

1.9.4 Nuclear Reactor

This represents that part of a nuclear power plant where U^{235} fuel is subjected to a controlled fission chain reaction, during which tremendous energy is generated.

The Fig. 1.16 shows the various components of a nuclear reactor and a heat exchanger.

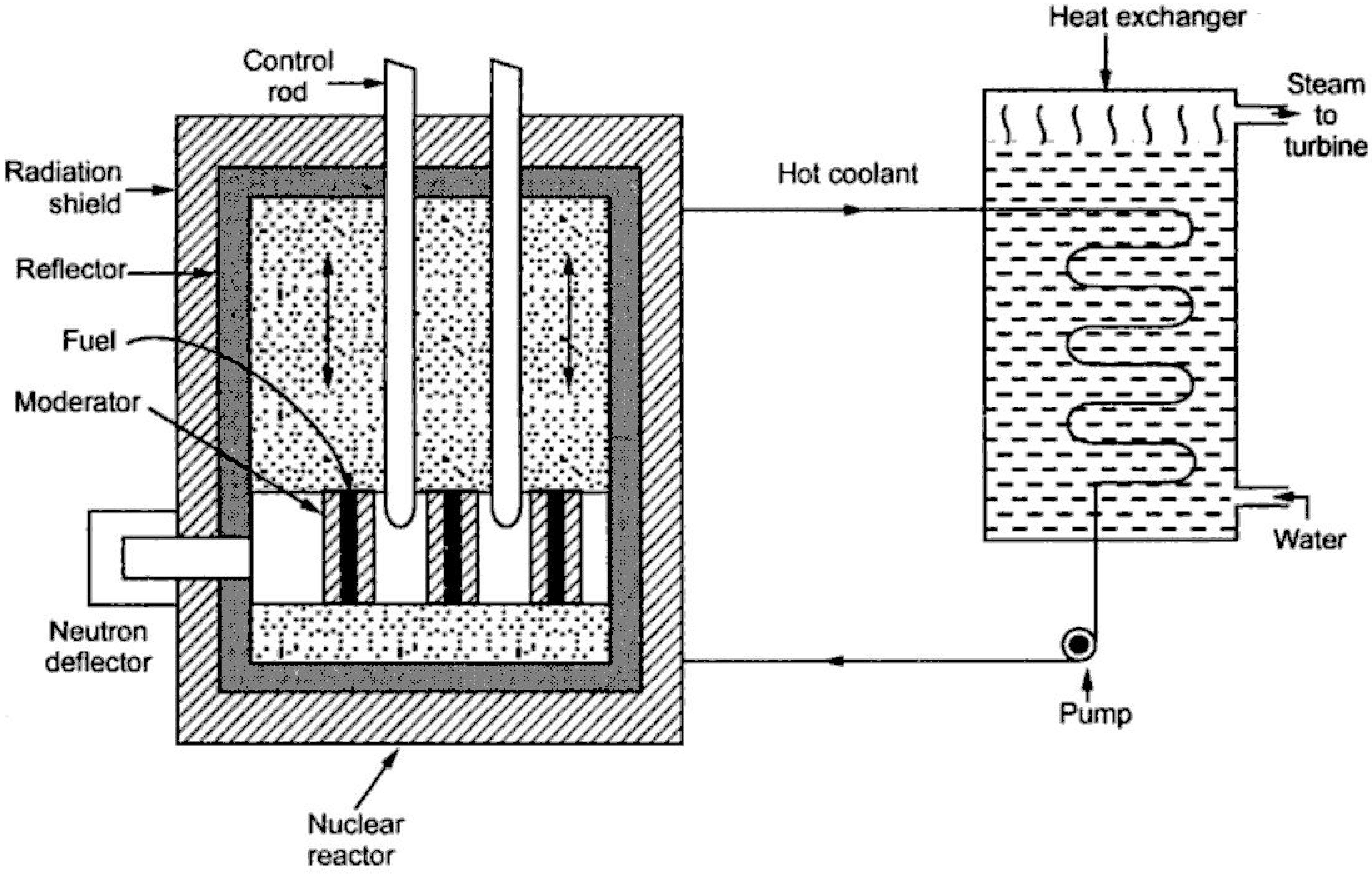


Fig. 1.16 Nuclear reactor and heat exchanger

The following are the components of the nuclear reactor.

1. Fuel : The commonly used fuel is uranium containing 0.7 % U^{235} or enriched uranium containing 1.5 - 2.5 % U^{235}. The fuel is used in the form of rods or plates which are surrounded by the moderators. The fuel rods are arranged in cluster and the entire assembly is called core. The minimum amount of the fuel required to maintain the chain reaction is called the critical mass.

2. Moderators : The main function of the moderators is to reduce the energy of neutrons evolved during fission. By slowing down the high energy neutron, the possibility of escape of neutrons is reduced while possibility of absorption of neutrons by fuel to cause further fission is increased. This also reduces the amount of fuel required for the chain reaction. The commonly used moderators are graphite, beryllium and heavy water. Some other functions of moderators include prevention of corrosion of fuel element, retain the radioactivity and to provide structural support.

3. Reflector : The reflector is placed around the core to reflect back some of the neutrons which may leak out from the surface of the core, without taking part in the fission. A blancket of reflector can reduce the critical mass required.

4. Control rods : The cadmium rods are used as control rods which are strong neutron absorber. Thus control rods can regulate the supply of neutrons for chain reaction. If the number of neutrons are not controlled, there is a possibility of explosion due to large amount of energy released. By pushing or pulling out of these rods, the rate of chain reaction and hence the heat produced can be controlled. The control rods are operated automatically as per the next requirement. The other material used for the control rods is boron or hafinium.

5. Coolant : The main purpose of the coolant is to transfer heat generated in the reactor core and use it for the steam generation. The coolant in the reactor keeps the temperature of fuel below safe level by continuous removal of the energy from the core. The liquid metals like sodium or potassium are used as coolants.

6. Radiation shield : The radiations of a radioactive substances are harmful to the human life. Hence radiation shield is used to prevent the escape of these radiations to the atmosphere. Generally 50 to 60 cm thick steel plate and few metres of the concrete outside are used as the radiation shield.

1.9.5 Heat Exchanger

It is a device which is used to exchange the heat from the primary circuit to the secondary circuit. The coolant carries the heat in the reactor to the exchanger where it is exchanged to the water, to convert water into steam. Thus the heat exchanger is nothing but a steam generator. Once the heat is exchanged, the coolant is fed back to the reactor, using the coolant recirculating pump.

1.9.6 Steam Turbine

The steam generated from the water in the secondary circuit is taken to the steam turbine through a main valve, where it is expanded. Due to this, turbine starts rotating and thus the heat energy is converted to a mechanical energy.

1.9.7 Alternator

The shaft of an alternator is coupled to the turbine shaft. Thus when the turbine rotates, the alternator starts rotating. The alternator converts mechanical energy into an electrical energy. The energy output of an alternator is given to the bus bars through transformer, circuit breakers and isolators.

1.9.8 Cooling Water Circuit

The expanded steam from the turbine is the exhausted steam which is taken to the condenser. In the condenser, the steam is condensed into water. For the condensation of steam, a flow of natural cold water is circulated through the condenser. This water takes heat from the exhaust steam. This hot water is passed through cooling tower, where it is again converted to cold water. Then it is recirculated through the condenser by pump. The condensed steam is then recirculated through the secondary circuit of exchanger, using the feed water pump.

1.9.9 Advantages

1. The amount of fuel required is very small.
2. There is saving in the transportation cost of fuel as fuel required is less.
3. It requires less space compared to any other type of the power plant.
4. The running cost per unit energy generated is lower than the thermal power plant.
5. It is very much economical.
6. There is a lack of environmental problems which are associated with the thermal power plant.
7. Large deposits of nuclear fuels are available so such plants can ensure continued supply of the fuel.
8. It ensures reliability of the operation.

1.9.10 Disadvantages

1. The fuel is very expensive.
2. The fuel is difficult to recover.
3. The capital cost is very high compared to other types.
4. The waste products are radioactive and can cause pollution.
5. The waste disposal problem is severe.
6. The maintenance charges are very high.
7. It is not suitable for the varying load conditions, as the reactor cannot respond instantly to the load fluctuations.
8. The fuel may be misused in weapons.

1.10 Gas Turbine Power Station

A power station which uses the gas turbine as the prime mover for the alternator, to produce an electrical energy is called gas turbine power station.

In a gas turbine power plant, air is used as a working fluid. The compressor is used to compress the air. The compressed air is taken to the combustion chamber. This adds heat to the air. This increases the temperature of the air. The air is heated either by burning the fuel or using the air heaters.

The hot and high pressure air is then transferred to the gas turbine. Here the air is expanded and drives the turbine. Thus the heat energy is converted to the mechanical energy. The rotating turbine drives an alternator which is coupled to the same shaft. The alternator converts the mechanical energy into an electrical energy. The output of an alternator is given to the bus bar through the transformer, circuit breakers and isolators.

The gas turbine plants are used as the standby plants for the hydro-electric stations.

The energy conversion involved in the gas turbine plant is shown in the Fig. 1.17.

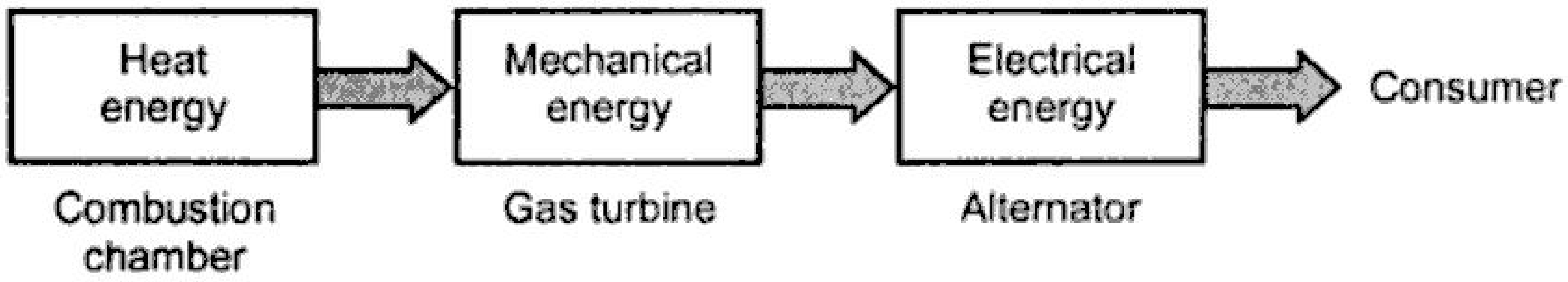


Fig. 1.17 Energy conversion

This plant can be situated anywhere and is not having any specific requirements for the selection of site.

1.10.1 General Arrangement of Gas Turbine Power Plant

The Fig. 1.18 shows the schematic arrangement of gas turbine power plant.

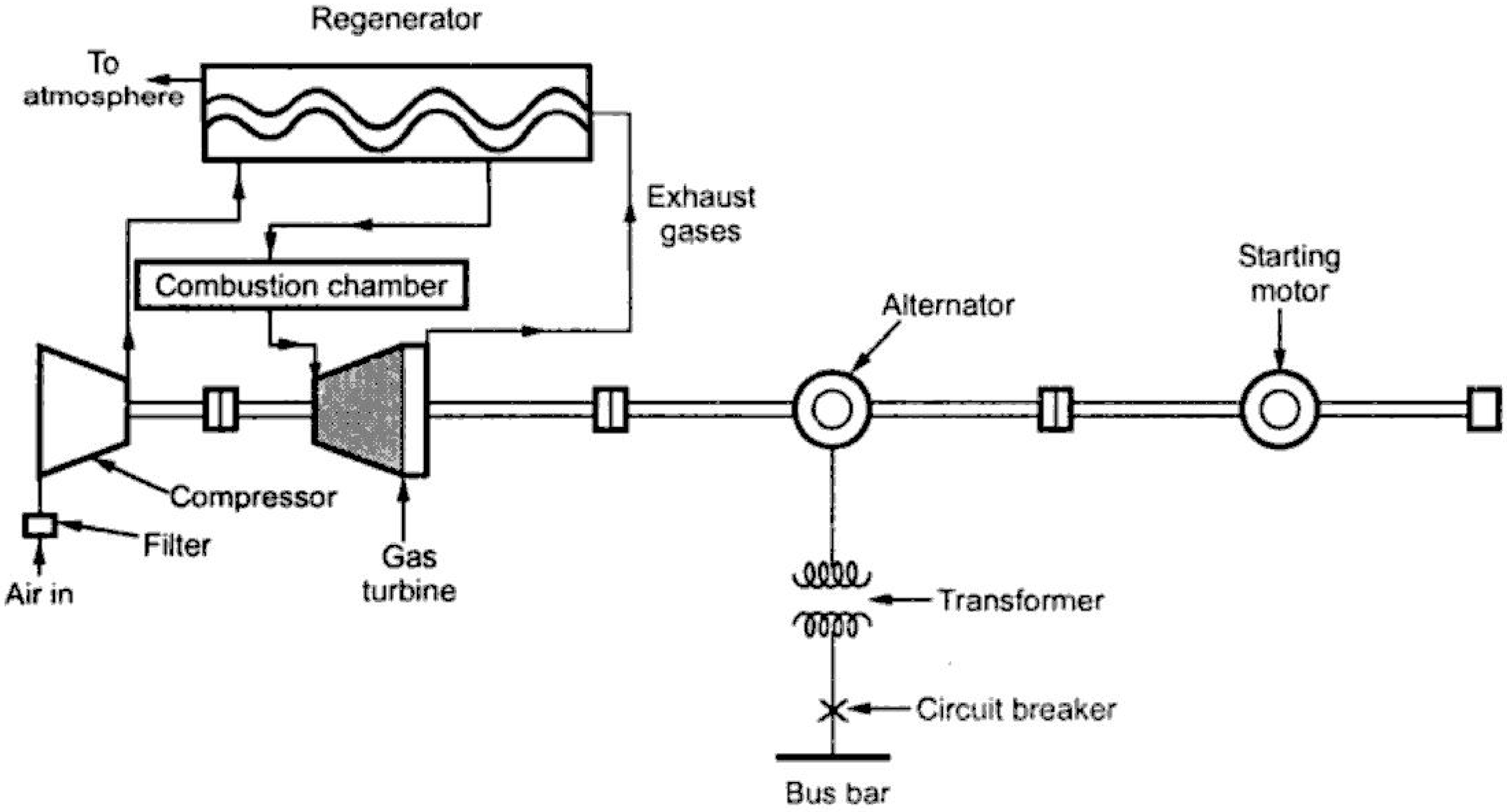


Fig. 1.18 Schematic arrangement of gas turbine power station

The main components of the plant are,

1. Compressor
2. Regenerator
3. Combustion chamber
4. Gas turbine
5. Alternator
6. Starting motor.

1.10.2 Compressor

The function of the compressor is to produce high pressure air. The compressor draws the air which is at the atmospheric pressure and increases its pressure. To remove the dust and other impurities from the air while taking in the compressor, it is passed through a filter. Thus at the output of the compressor, a very high pressure pure air is available, which is necessary for further processes. Generally a rotary type of compressor is used.

1.10.3 Regenerator

The exhaust gases from the turbine are given to a regenerator. The regenerator is a device which recovers the heat from the exhaust gases of the turbine, before the gases are released to the atmosphere. A regenerator consists of a shell and a tube. The exhaust gases are made to flow inside the nest of the tubes while the air flows outside the tubes in the shell in opposite direction. Thus the air is heated up due to the heat given by the exhaust gases. Thus the compressed air is heated before entering the combustion chamber. The regenerator reduces the requirement of the fuel for the combustion to produce heat and improves the plant efficiency. The heated compressed air is taken to the combustion chamber.

1.10.4 Combustion Chamber

The function of the combustion chamber is to add large amount of heat to the compressed air. In the combustion chamber the heat is produced by burning the fuel like oil. The oil is injected in the chamber through a burner, at a high pressure. Due to this, the temperature of the chamber becomes very high about 3000 °F. Thus the air also attains very high temperature in a combustion chamber. Before taking to the gas turbine, the air is suitably cooled, to 1500 °F.

1.10.5 Gas Turbine

The air at high pressure and temperature, available at the output of the compressor, is given to the gas turbine. These gases while passing over the blades expand and do the mechanical work. This drives the turbine and thus the heat energy is converted to a mechanical energy. The temperature of the exhaust gases leaving the turbine is about 900 °F.

1.10.6 Alternator

An alternator is coupled to the gas turbine. Thus when the turbine starts rotating, it drives the alternator. The alternator converts the mechanical energy into an electrical energy. The output of the alternator is given to the bus bars through the transformer, circuit breakers and the isolators.

1.10.7 Starting Motor

The compressor is required to be started first before turbine starts. Hence an electric motor is mounted on the same shaft of turbine and compressor. The motor is operated by the batteries. Once the compressor starts, the entire unit starts operating and the turbine starts rotating. Then the turbine drives the compressor and hence motor can be swiched off. Thus in running condition, the motor is not required hence it is called starting motor.

1.10.8 Advantages

1. Much compact and less space required compared to steam power plant.
2. Simple in construction compared to the steam power plant, due to absence of boiler and other equipments.
3. It can be started very quickly and has very short starting time.
4. The fuel consumption during starting and shutting down is very low.
5. The water required is less as condenser is absent.
6. Due to the absence of reciprocating masses such as piston, there are no vibrations and not much noise.
7. The initial and operating costs are much smaller.
8. The maintenance charges are small.
9. There is much higher output per unit.
10. The shaft speeds can be much higher.
11. The standby losses are absent because the parts like boiler are absent which are on though the steam turbine is on no load.
12. The number of workers required is very less.
13. The partial or full automation is possible.
14. Very heavy foundations and structures are not required.
15. The components and circuits can be arranged so as to give most economical results.

1.10.9 Disadvantages

1. The compressor is required to start first hence an extra motor additional power is required.
2. The part of the turbine work is used to drive the compressor hence net output is low.
3. The overall efficiency is very low as large amount of heat gets wasted through exhaust gases though regenerator is used.
4. The life of the combustion chamber is less due to very high temperatures.

1.11 Solar Power Plant

The surface of the earth receives from sun about 10^{14} kW of solar energy. The amount of solar energy reaching the earth is not easily convertible. There are two obvious obstacles in harnessing solar energy. First it is not constantly available on earth and secondly the energy is diffused. Therefore it requires a large capital investment for conversion apparatus.

Flat Plate Solar Collector

Fig. 1.19 shows a flat plate collector which consists of following components.

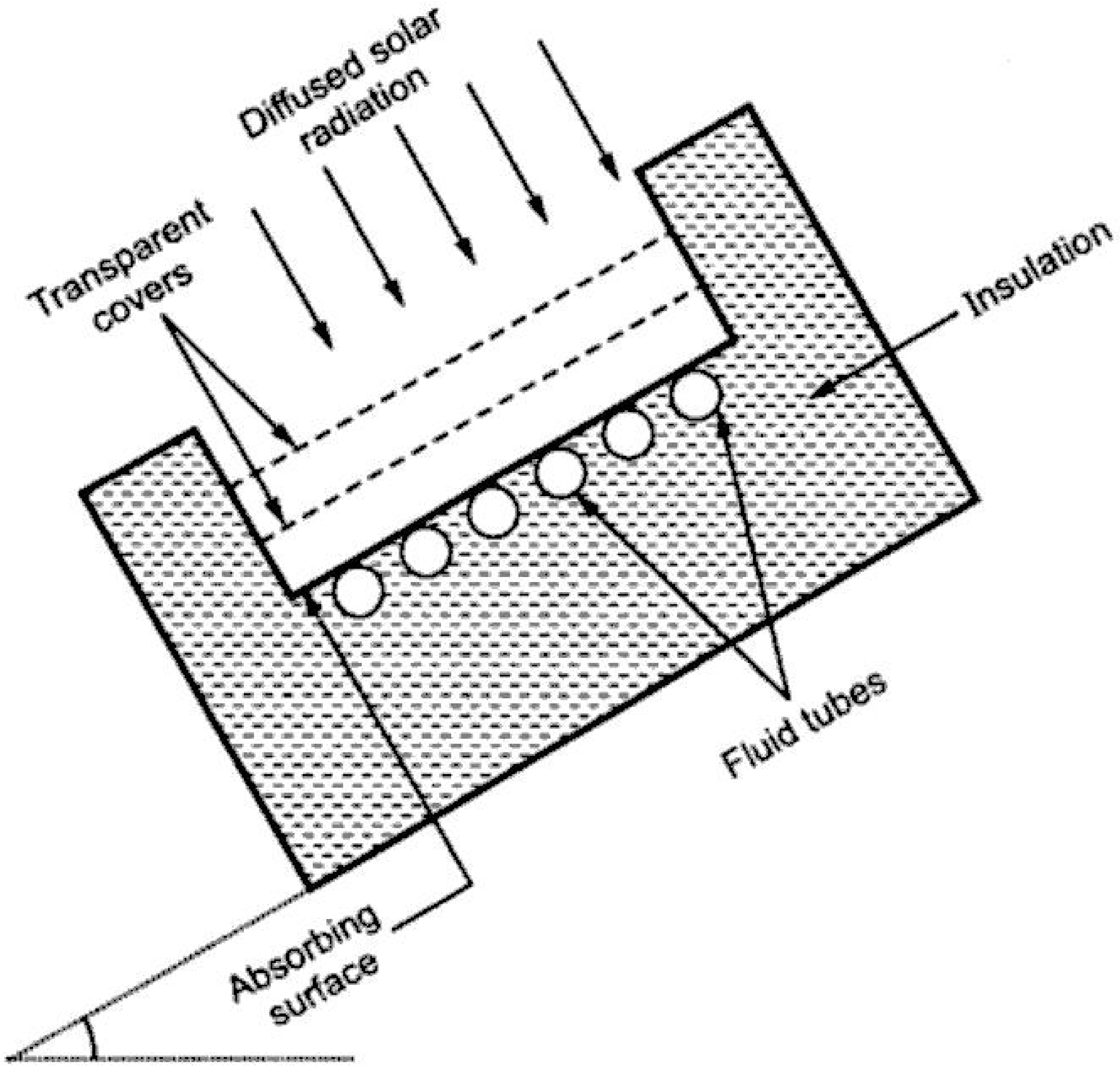


Fig. 1.19 Flat plate solar collector

i) An absorber plate : It intercepts and absorbs solar radiations.

iii) Transparent covers : These are one or more sheets of solar radiation transmitting materials and are placed above the absorber plate. They allow solar energy to reach absorber plate while reducing convection, conduction and re-radiation heat losses.

iv) Insulation : It is placed beneath absorber plate. It minimizes and protects absorbing surface from heat losses.

Solar Power Plant

Fig. 1.20 represents a schematic diagram of solar power plant.

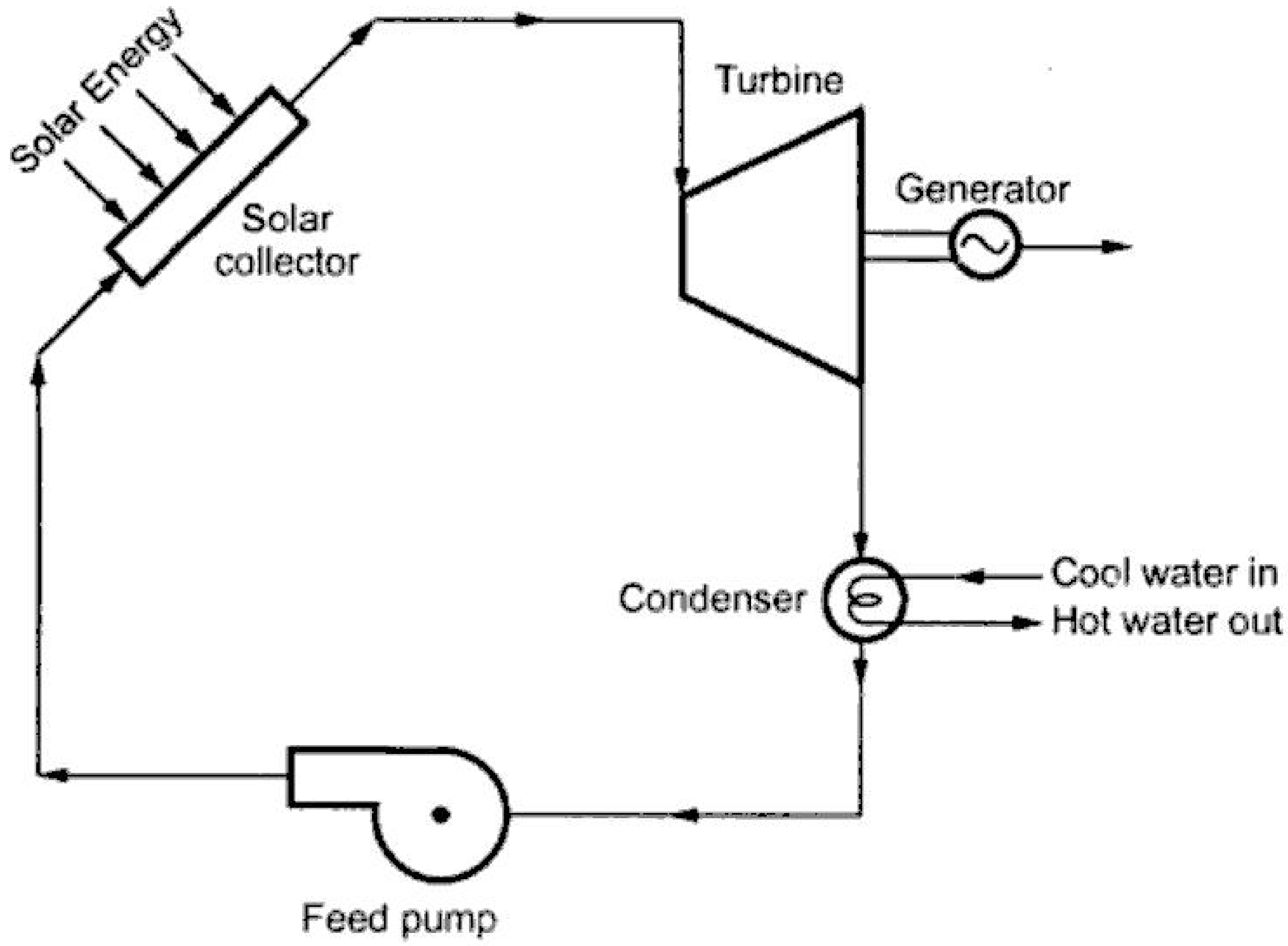


Fig. 1.20 Solar power plant

The basic components of solar power plant are also exactly identical to thermal power plant except boiler is replaced by a flat plate solar collector.

The energy from solar radiation is collected and utilized to generate a steam to run steam turbines. For obtaining reasonably high efficiency, concentration type of collectors are used when steam is used as working fluid. The cost of concentrating collector is more than flat plate collector. Therefore, new working fluid whose saturation temperature is lower than that of water at considerably high pressures are normally used in this type of power plant. But the thermal efficiency of the plant will be low due to low temperature range.

This is more suitable in rural areas for house lighting and water pumping for irrigation purpose.

Energy Conversions

Heat energy ⇒ Mechanical energy ⇒ Electrical energy

1.11.1 Advantages

Solar energy has following advantages.

1) Solar radiation does not disturb ecological balance.

2) It is available freely in nature.

3) It is non-depleting source.
4) It is easily available all over the wind.

1.11.2 Disadvantages

Following are disadvantages of solar energy.

1) Collections and conservation of solar energy into useful forms must be carried out over a large area which requires a large capital investment for conversion.
2) Such power plants require direct light and are not operative when the sun is even partly covered with clouds.
3) Reflecting surfaces undergo deterioration with passage of time.
4) These power plants are uneconomical.

1.12 Wind Power Plant

Wind flow is created as an effect of solar energy which creates low and high pressure regions on the earth due to the heating. This wind is used to run a wind mill which in turn drives a generator to produce electricity. In India, high wind speeds are available in coastal areas of Sourashtra, Western Rajsthan and some parts of central India. In Maharashtra wind mills are erected at various places like Brahmanwel in Dhule district, near Supa in Ahmednagar district and Chalkewadi, Thoseghar in Satara district.

Fig. 1.21 shows a schematic arrangement of a horizontal axis wind-electric generating power plant. The various parts of this power plant are -

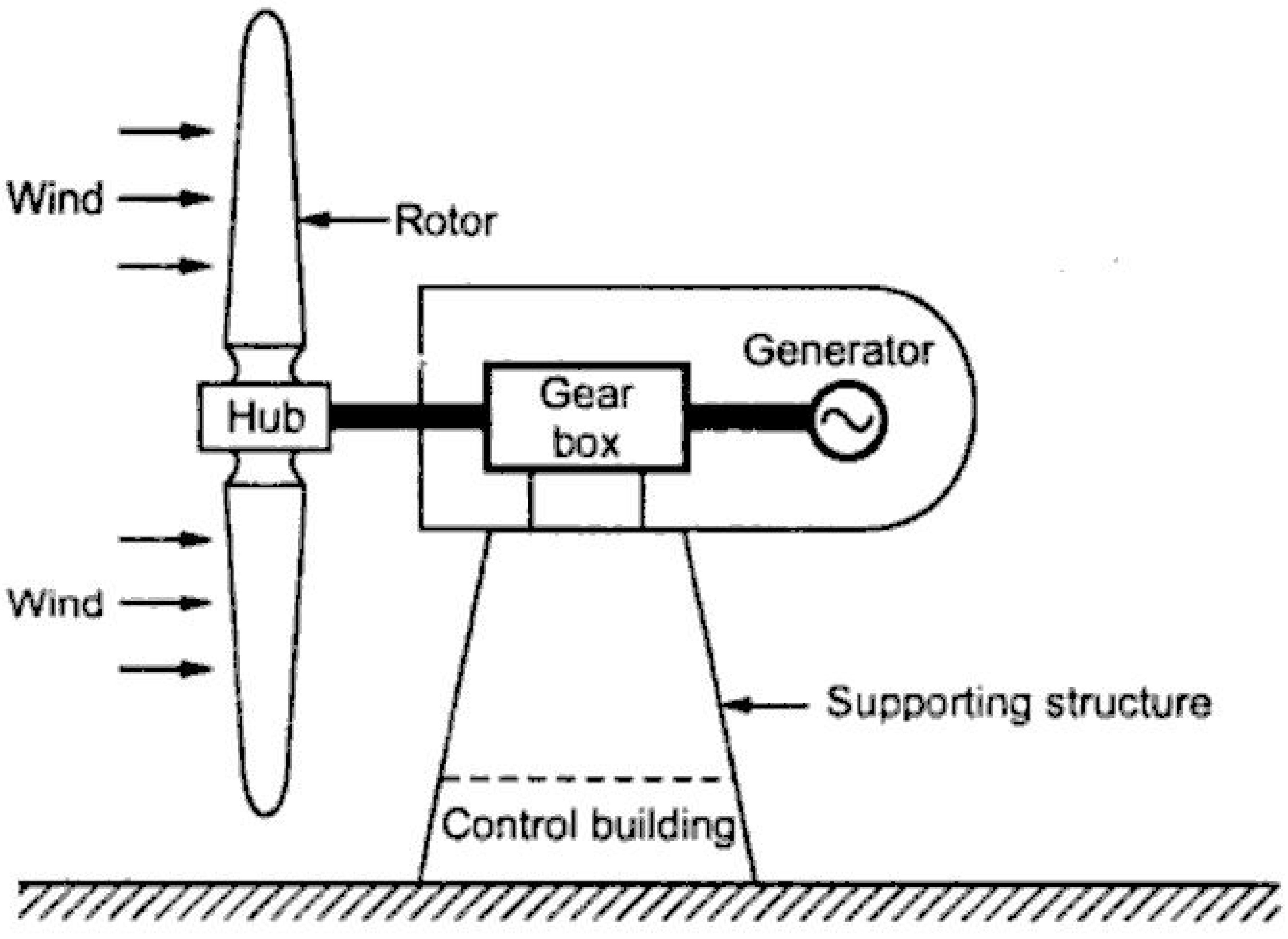


Fig. 1.21 Horizontal axis wind mill

1) Wind rotor
2) Gear box
3) Electrical generator
4) Supporting structure.

1) Wind rotor : These blades (rotors) are attached on the hub which is connected to shaft. These blades have specific design.

2) Gear box : The shaft of the hub acts as input to the gear box. R.P.M. of the shaft is increased in the ratio upto 1 : 100 in the gear box, to produce electricity.

3) Electrical generator : The shaft is further connected to generator shaft. When shaft rotates, the generation shaft inturn rotates producing electrical energy in generator. Thus mechanical energy is converted into electrical energy.

4) Supporting structure : The supporting structure is designed to withstand the wind load. Its type and height is related to the cost and transmission system incorporated. Horizontal axis wind turbines are mounted on towers so as to be above the level of turbulence and other ground related effects.

Conversion of energy

Kinetic energy ⇒ Mechanical energy ⇒ Electrical energy

1.12.1 Advantages

Wind energy offers following advantages.

1) It is available at free of cost.
2) It is available in many off-shore, on-shore, remote areas helpful in supplying electric power to remote areas.
3) It is cost effective and reliable.
4) It supplies energy in rural areas.
5) It does not cause pollution during energy generation.
6) It is economically competitive.

1.12.2 Disadvantages

Following are the disadvantages of wind energy.

1) It has low energy density.
2) It is favourable in geographical locations away from cities.
3) The supply is variable, unsteady, irregular, intermittent and sometimes dangerous.
4) Wind turbine design, manufacture and installation have proved to be complex due to widely varying atmospheric conditions in which they have to operate.
5) It has high capital cost per kWh.
6) It requires energy storage batteries which indirectly and substantially contribute to environmental pollution.
7) Wind farms can be located only in vast open areas which are away from load centres.

1.13 Wave Energy

In India, a vast source of energy is available with hundreds of kilometres of coast line. The power in the wave is proportional to the square of the amplitude and to the period of motion. Therefore, the waves having long period (~ 10 s) and large amplitude (~ 2 m) are of considerable interest for power generation. Eventhough the engineering problems associated with wave-power are formidable, the amount of energy that can be harnessed is large and development work is in progress. On an average, it is estimated that about 10 kW of power is available in ocean waves and that the total amount of wave power is of the order of 2×10^6 MW.

1.14 Ocean Thermal Energy Conversion (OTEC)

Tropical oceans collect and store very large amount of solar energy. Utilization of this energy with associated temperature difference and conversion of this thermal energy into work and hence into electricity is the basis of ocean thermal energy conversion (OTEC) systems.

Estimated potential of ocean thermal power in India is 50000 MW.

1.15 Tidal Energy

Tides are generated by the gravitational attraction between the earth and the moon. They arise twice a day. In mid-ocean, the tidal range is only a metre or less, but in some coastal estuaries, it is much greater.

In a tidal power station, water at high tide is first trapped in an artificial basin and then allowed to escape at low tide. The escaping water is used to drive water turbines which in turn drive electrical generators.

Major sites in India, where preliminary investigations have been carried out are Bhavnagar, Navalakhi, Diamond Harbour and Ganga Sagar.

1.16 Geothermal Energy

The geothermal resource is the heat stored locally at depths of 1 or 2 km in the earth's mantle in hot dry rocks having no contact with water. When ground water comes in contact with these hot rocks, either dry steam or wet steam and water are formed. After drilling such locations, the dry or wet steam emerges at the surface where its energy can be utilized either for generating electricity or for space heating.

In India, geothermal resources in the form of steam and hot water are available along the west coast, in Ladakh and in parts of Himachal pradesh.

1.17 Biofuels

Biomass is nothing but the material of all plants and animals. This can be transformed by chemical and biological processes into intermediate products like methane gas, ethanol liquid or charcoal solid.

Biofuels can be used to produce electricity in below mentioned two ways :

a) By burning the biomass in a furnace to generate steam which will be used to drive turbines.

b) By allowing fermentation in sites or in special anaerobic tanks, to produce methane gas. This can be used as a fuel for household stores or in gas turbines.

Biofuels have a potential to meet about 5 % of the electricity requirements by exploiting all forms of these household and industrial wastes, sewerage, sledge and agricultural wastes like cow dung, sugarcane, chicken litter etc.

1.18 Distributed Generation

When small generators of capacities around 2 - 50 MW output are installed at typical points in the area such that each of these generators supply power to a small number of consumers nearby then it is called distributed generation. The generators may be operated through renewable energy sources such as solar, wind or gas turbines, small hydro or micro turbines as these are most economical choices. Dispersed generation is use of still smaller generating units of less than 500 kW and used for individual houses or small business. The distributed or dispersed generators may be standalone or grid connected depending on the requirement.

Distributed generation proves to be economical as it requires no transmission network and reduced need of distribution equipments. Another advantage is this generation is portable or compact as compared to big power stations located far away from consumers. Also they are modular and relocatable. The fuel cells and microgas turbines are two new types of techniques evolved in distributed generation.

The main challenge is to upgrade existing technology and to promote development, demonstration of new and upcoming technologies for widespread adaptation of distributed generation.

1.19 Power Plant Economics

For any developing country, the energy sector plays very important role in its growth. The progress of the country is indicated by its strong economic position which is highly dependent on its energy policy. The electrical supply company supplying power to consumers is a commercial enterprise which should have strong foundation to stay in competative business market and to get capital for meeting additional demands.

The electrical supply company is however different from the usual business enterprise in the following aspects.

i) Eventhough the supply company is public utility service they do not have direct competition. Mostly this sector comes under state governments and hence limits the earnings that can be made.

ii) There is obligation on the supply company to provide the service to whatsoever applies for it.

iii) The service provided by the supply company cannot be withdrawn from the consumers without regulatory approval.

Considering the above aspects, there is big responsibility on utility systems to achieve economy in such a way that the cost per unit is as low as possible and at the same time the supply company gains profit and ensure reliable service while designing and building the power station.

The calculation of cost of electrical energy is a complex task. There are several factors affecting this cost. Few of these factors are land and equipment cost, the interest on the capital investment, depreciation on the equipment etc. Hence while deciding per unit cost a thorough study of various economic aspects of electric supply is to be made.

To understand this fact, let us consider an example. Suppose that an electric supply company has to provide power to particular area. For this purpose correct idea of load requirements must be known for that area. After this the next question is how to get this power. There are various types of generating stations. The important stations are thermal hydral and nuclear stations. Number of factors are to be considered like suitable site, cost of fuel and its availability, nature of load to be supplied, environment cleanliness etc. while selecting the generating station.

The next important factor is the load on the power station is never constant but keeps on changing with time as demands are different. The variations in load are to be predicted initially and based on the maximum demand on the station, that much minimum capacity of the generating station is selected. Only selection is not sufficient but it has to maintain its constant service and reliability. Only one unit cannot serve this purpose as it is not practical and economical too.

To solve this problem, an alternative is to select size and number of generating sets in such a way as to fit in the load curve or in the load demands as closely as possible. But again the problem is increase in operational problems and maintenance costs with large number of generating units. Similarly the capital cost of the system also increases which will not lead to lower per unit cost of electricity. Hence there must be compromise in selecting the size and number of generating units for a station.

The above example shows the importance of economics of power generation and its study. In this chapter we are studying the economic aspects of power plant and its selection along with the important terms commonly used in the system operation.

1.20 Terms Commonly used in System Operation

Before studying the economics of generation let us see few terms which are commonly used in system operation.

1) Connected load : The sum of continuous ratings of all the equipments which are connected to the supply system is called connected load.

The load of Thousands of consumers is supplied by a power station. The load means various equipments and apparatus present in consumers premises. If the summation of these continuous ratings of all the equipments is made then it forms the connected load of that consumer. The sum of connected loads of all the consumers is the connected load to the power station

2) Maximum demand : It is defined as the largest demand of load on the generating station during a specified period. The load on the generating station is never constant but keeps on varying from time to time. The demand of load which is maximum of all, during a given period, forms maximum demand.

Maximum demand is normally less than the connected load because the connected load to the system of various consumers is not switched on at the same time. The installed capacity of the station is decided from the maximum demand. It is quite obvious that the power station must be able to supply the maximum demand.

3) Demand factor : It is defined as the ratio of maximum demand to its connected load. Mathematically it is given as,

$$\boxed{\text{Demand factor} = \frac{\text{Maximum demand}}{\text{Connected load}}}$$

We have seen that the maximum demand is generally less than its connected load hence the demand factor is less than unity. This factor is an important consideration in deciding the capacity of the plant equipment.

Consider for example a building with following connected load.

Number of lamps = 200 each of 40 W = 8 kW

Power points = 150 each of 500 W = 75 kW

Lift = 10 kW

Pump = 10 kW

∴ Total connected load = 8 + 75 + 10 + 10 = 103 kW

This is the total connected load of the building but it is not switched on at the same time. Consider that 100 lamps, 100 power points, lift and pump are on at the same time which is say maximum possible condition of the load for that building. All the other load demands are less than this peak.

$$\therefore \quad \text{Maximum demand} = 100 \times 40 + 100 \times 500 + 10 + 10$$
$$= 4\text{ kW} + 50\text{ kW} + 20\text{ kW}$$
$$= 74\text{ kW}$$

Hence the demand factor for this building is

$$\text{Demand factor} = \frac{\text{Maximum demand}}{\text{Connected load}} = \frac{74\text{ kW}}{103\text{ kW}}$$
$$= \mathbf{0.7184}$$

At it is ratio of two similar quantities it is not having any unit.

Similarly the demand factor of the generating station is also calculated from the knowledge of maximum demand and the connected load on that power station.

4) Average load or average demand : It is defined as the average of the loads occurring on the power system or generating station in a given period. The period may be day or month or year. Mathematically it is given as,

$$\text{Daily average load} = \frac{\text{Number of units generated in a day (kWh)}}{24\text{ hours}}$$

$$\text{Monthly average load} = \frac{\text{Number of units generated in a month (kWh)}}{\text{Number of hours in a month}}$$

$$\text{Yearly average load} = \frac{\text{Number of units generated in a year (kWh)}}{8760\text{ hours}}$$

The average demand on the station is thus corresponds to particular period.

5) Load factor : It is defined as the ratio of average load to the maximum demand during a given period. Mathematically it is given as,

$$\boxed{\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}}}$$

Depending upon the consideration of time, the load factor may be daily, monthly or yearly. Suppose the operation time of plant is say T hours.

$$\therefore \quad \text{Load factor} = \frac{\text{Average load} \times \text{T}}{\text{Maximum demand} \times \text{T}}$$

$$\therefore \quad \boxed{\text{Load factor} = \frac{\text{Units generated in T hours}}{\text{Maximum demand} \times \text{T}}}$$

The yearly load factor is defined as,

$$\text{Yearly load factor} = \frac{\text{Number of units supplied in a year}}{\text{Maximum number of units that can be supplied}}$$

$$\therefore \quad \boxed{\text{Yearly load factor} = \frac{\text{Number of units supplied in a year}}{\text{Maximum demand} \times 8760}}$$

The load factor is always less than 1 as average load is smaller than maximum demand. This is the key factor in deciding the overall cost per unit generated. With increase in load factor, maximum demand on the station will be less. We have already seen that the plant must supply its maximum demand. Thus with lower maximum demand, the capacity of the plant also lowers which reduces cost of plant with ultimate effect of reduction in cost per unit generated.

Monthly load factor is given by,

$$\therefore \quad \boxed{\text{Monthly load factor} = \frac{\text{kWh or units supplied in a month}}{\text{Maximum demand} \times 24 \times 30}}$$

The load factor defined as above corresponds to the supplier and may sometimes referred as undertaking load factor.

6) Diversity factor : To improve the working of the generating station the loads must be diversed or staggered. The maximum demand of various types of consumers which is supplied by a power station does not occur at the same time. Hence the maximum demand on the generating station is always less than the sum of individual maximum demands.

The diversity factor is thus defined as the ratio of sum of individual maximum demands to the maximum demand on power station. Mathematically it is defined as,

$$\boxed{\text{Diversity factor} = \frac{\text{Sum of individual maximum demands}}{\text{Maximum demand on power station}}}$$

The diversity factor is always greater than 1 if defined in above way. Greater the diversity factor, lesser is the cost of generation since more diversity factor means less maximum demand which corresponds to lesser plant capacity which reduces cost of plant and hence that of generation.

For understanding this factor, let us consider an example. Let us consider that a generating station is supplying power to following various consumers.

Consumer 1	Industrial	6000 kW
Consumer 2	Residential	1000 kW
Consumer 3	Commercial load	2000 kW
Consumer 4	Private load	500 kW
Consumer 5	Municipal load	400 kW
Consumer 6	Agricultural load	100 kW

$$\text{Diversity factor} = \frac{\text{Sum of individual maximum demand}}{\text{Maximum demand on power station}}$$

$$= \frac{6000+1000+2000+500+400+100}{6000}$$

$$\text{Diversity factor} = \frac{10000}{6000} = \mathbf{1.66}$$

The maximum demand of each category of load is not occurring at the same time. If it is occurring at the same time then the station has to supply this demand for short duration. The average load on the station is around 50 %. Hence the plant generators will remain idle in the remaining time after supplying this peak demand and this will not be economical operation of the plant. Under such case the consumers are advised to diverse their loads or advised to ask their maximum demands at different times then the operation of station will be economical. In case of industrial load or municipal load such diversification of load is possible. So if the maximum demand is made smaller then it will be economical operation.

In the above example if instead of 6000 kW, the maximum demand is made 5000 kW by diversification of load then the new diversity factor is calculated as,

$$\text{New diversity factor} = \frac{\text{Sum of individual maximum demands}}{\text{Maximum demand}}$$

$$= \frac{10000}{5000} = 2$$

Key Point : *In summery, we can say that by diversing the load, the capital cost of the plant and hence cost per unit can be reduced. similarly the alternators in the plant can be operated to their maximum capacity.*

7) Capacity factor : It is defined as the ratio of actual energy produced to the maximum possible energy that could have been produced during a given period.

$$\boxed{\text{Capacity factor} = \frac{\text{Actual energy produced}}{\text{Maximum energy that could have been produced}}}$$

If period of operation of plant is say T hours.

$$\text{Capacity factor} = \frac{\text{Average demand} \times T}{\text{Maximum demand} \times T}$$

$$= \frac{\text{Average demand}}{\text{Plant capacity}}$$

For a period of one year,

$$\boxed{\text{Annual capacity factor} = \frac{\text{Annual kWh output}}{\text{Plant capacity} \times 8760}}$$

Thus it can be seen that plant capacity factor indicates the reserve capacity of the plant. A power station should have some reserve capacity for increased load demand in the future. Hence the installed capacity of the plant is greater than the maximum demand.

Reserved capacity = Plant capacity – Maximum demand

If plant is not having any reserved capacity then plant capacity is equal to maximum demand which indicates that capacity factor and load factor are same.

Some important terms related to this factor are as given below.

i) Firm power : It is the power which is available always even under emergency condition.

ii) Cold reserve : It is the reserve generation capacity which is available for service but not in operation.

iii) Hot reserve : It is the reserve generation capacity which is in operation but is not in service.

iv) Spinning reserve : It is that generating capacity which is connected to the bus and ready to take load.

8) Plant use factor : It is defined as the ratio of units generated (kWh) to the product of plant capacity and the number of hours for which the plant was in operation.

$$\boxed{\text{Plant use factor} = \frac{\text{Station output in kWh}}{\text{Plant capacity} \times \text{Hours of use}}}$$

This factor is an indication of best possible and effective utilization of generating station. But it does indicate the idle time of the plant.

1.21 Variable Load on Power Station

We have already seen that the load on the generating station is never constant but varies from time to time as the demands from the consumers are variable. Ideally it is required that the load should be of constant magnitude and for fixed duration which is not possible in practice. Thus as the load demand of various consumers goes on changing continuously, the load on the power station is always variable which has its own effects which are discussed below.

The first effect of variable load is the necessity of additional equipment for meeting the changing load demand. With increase in power demand, the output of the generating station must be increased which requires corresponding increase in supply of raw materials. Thus additional equipments are required to perform this task.

The second effect of variable load is increase in cost of production of electrical energy. Generally the alternator has its maximum efficiency near its rated capacity. Now if alternator is lightly loaded during periods of low demand then its efficiency will be poor. In such cases alternators of different capacities are to be installed in the plant so that they can be operated at their maximum efficiency. This increases cost per kW of the plant capacity as well as area required. This also increases production cost of energy.

1.22 Load Curve

We have already seen that the load on the power station goes on changing with respect to time. So if these variations are plotted then curve obtained is called load curve. From the load curve following information is obtained,

1. The variation of load on the plant during different hours of a day.
2. The maximum and minimum values of load during a day.
3. Maximum and minimum values of load during a year.
4. Average load on the station during a year.
5. It gives the indication whether the station is working efficiently or not.

The load curve may be a daily, monthly or yearly on the basis of whether the load variations are plotted during a day, month or a year.

In a daily load curve, the load variations are plotted against time on graph after recording their values on half-hourly or hourly basis. Fig. 1.22 shows a typical load curve on the plant. From this figure the general character of the load can be obtained which is not possible with tabulated values.

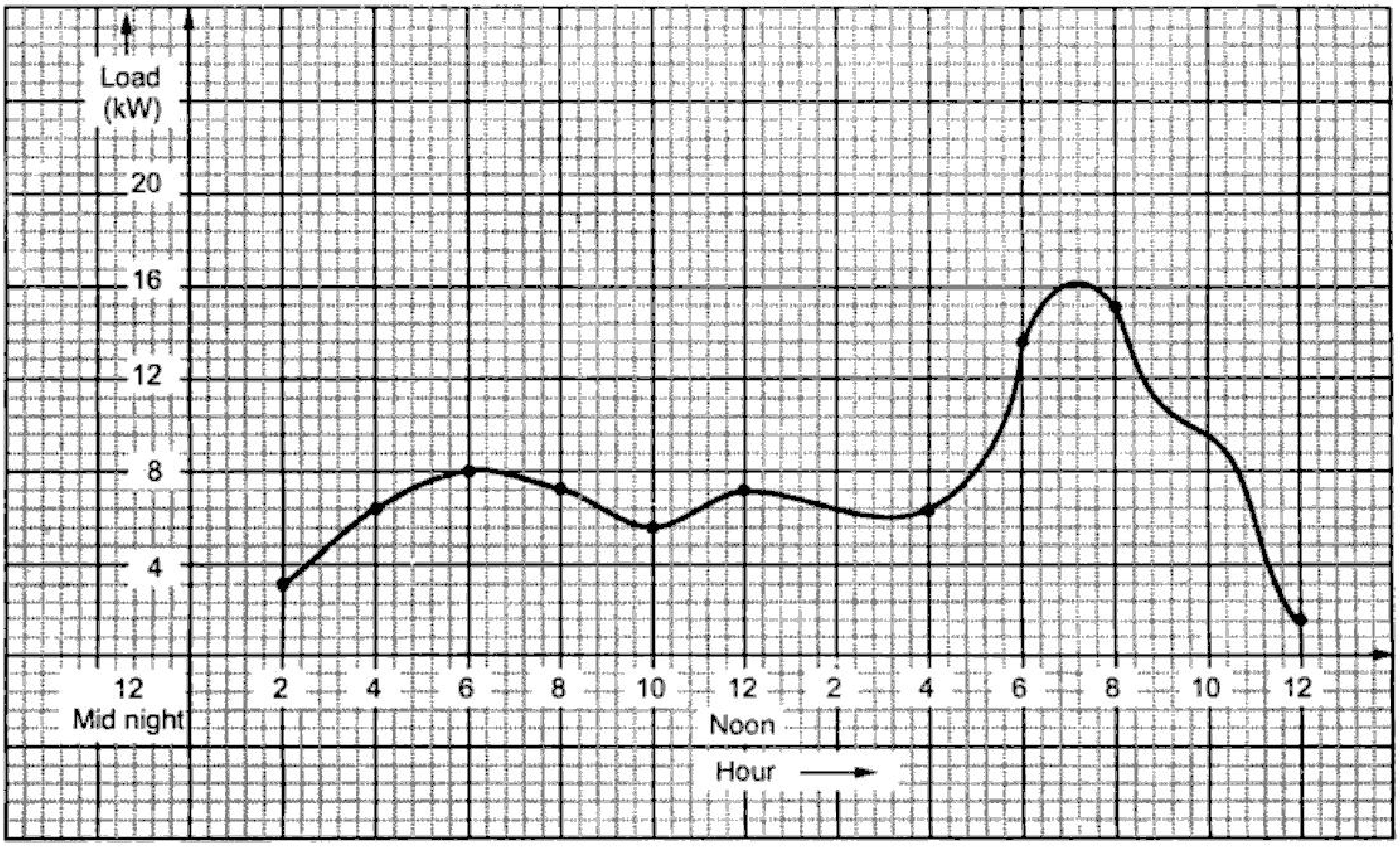


Fig. 1.22 Typical daily load curve

It can be seen from the above curve that the maximum load occurs during the period between 6 p.m. to 8 p.m. whereas it is minimum in the afternoon period.

The monthly load curve can be obtained from daily load curve of that month. The average values of load at different periods of the day for the month is calculated and then the curve is plotted on the graph. This curve helps in determining the rates of energy.

The yearly load curve can be obtained from monthly load curve of that year. The annual load factor can be determined from this curve.

Now consider the above daily load curve. The area under this curve gives the number of units generated in the day.

Units generated in a day = Area under daily load curve

The highest point on the load curve indicates the maximum demand on the station for that day.

If the area under this curve is divided by total number of hours gives the average load on the station.

$$\therefore \quad \text{Average load} = \frac{\text{Area under daily load curve in kWh}}{\text{Number of hours in a day (24)}}$$

The load factor can also be calculated by taking a ratio of area under load curve to the total area of the rectangle in which the curve is contained.

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}} = \frac{\text{Average load} \times 24}{\text{Maximum demand} \times 24}$$

$$\therefore \quad \text{Load factor} = \frac{\text{Area under daily load curve (kWh)}}{\text{Total area of rectangle in which curve is contained}}$$

The size and generating units can be obtained from the load curve. The number of generating units are such as to fit the load curve. This aids in operating the generating units near or at maximum efficiency.

Depending on load demands obtained from the load curve, the generating units can be put in operation. This sequence and time for which units are operated can be decided from the information obtained from load curve. Thus the operating schedule of the plant can be prepared from load curve.

1.22.1 Plotting of Load Curve

Before plotting the load curve, the load is divided into number of categories. The load is classified into following different categories.

1) Public places load
2) Private or residential load
3) Cinema hall load
4) Shops, hostels and hospital load
5) Railway load
6) Water works load
7) Industrial load
8) Street light.

The load sheet is prepared for each locality. Then the total of each type of load in different hours in a day are obtained.

The reading taken for each types of load during different hours of a day are plotted on a graph which gives the load curve.

The load curve goes on changing from summer to winter. In the summer season, there is a load of refrigerators, fan and air conditioning. As the light load comes up after sunset the maximum demand of load will be between 8.00 p.m. to 10.0 p.m. In winter the load conditions are different and correspondingly peak demands are different.

The typical load curves for Delhi in summer, winter and monsoon season are shown in following Fig. 1.23, 1.24 and 1.25.

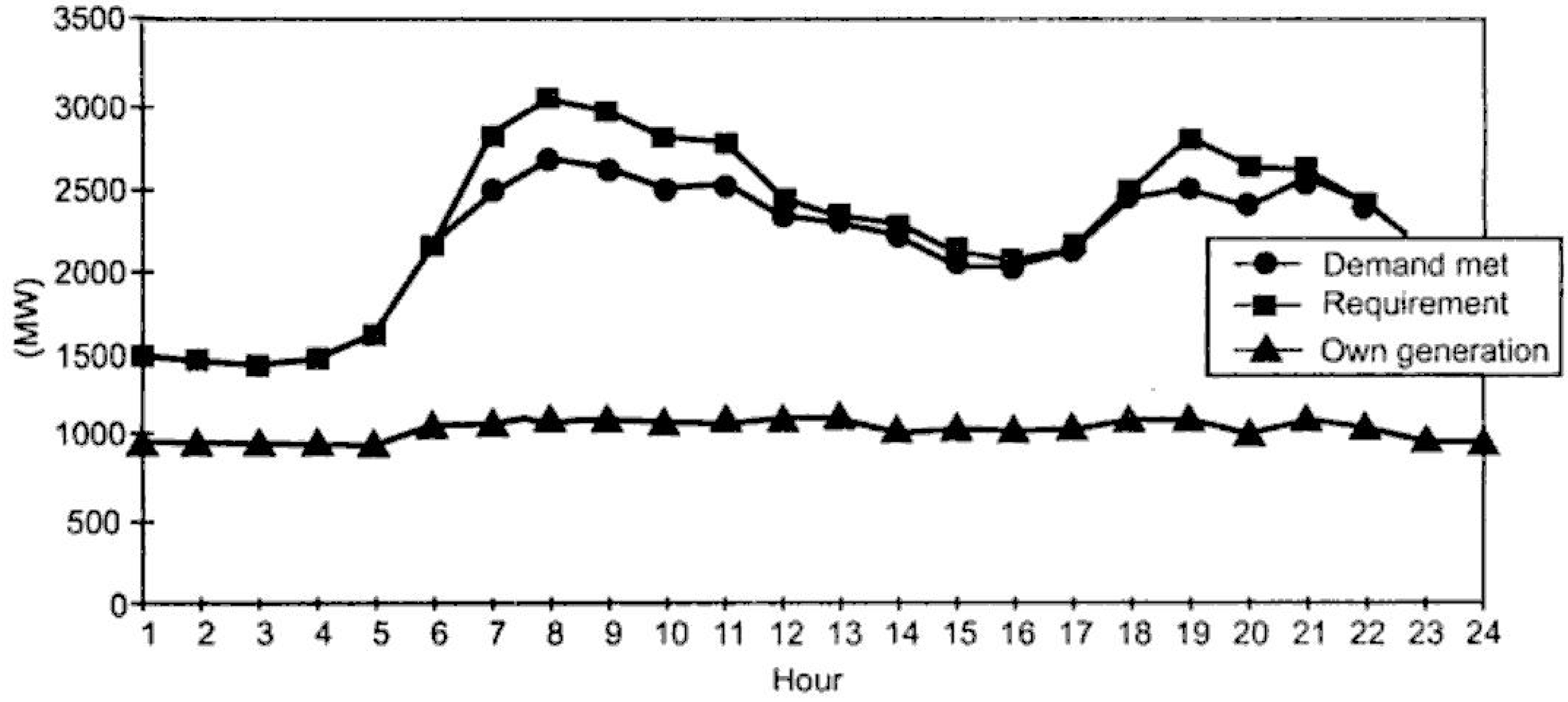


Fig. 1.23 Winter season

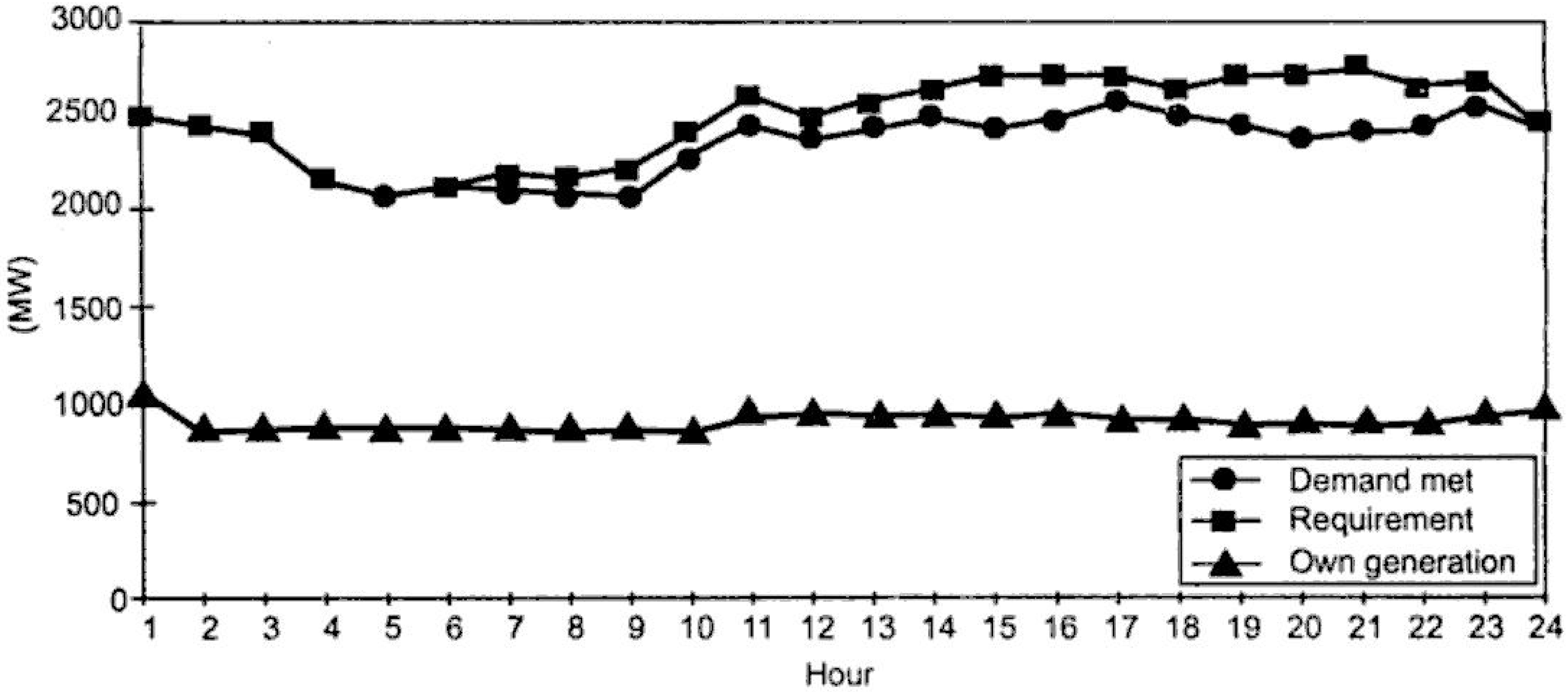


Fig. 1.24 Summer season

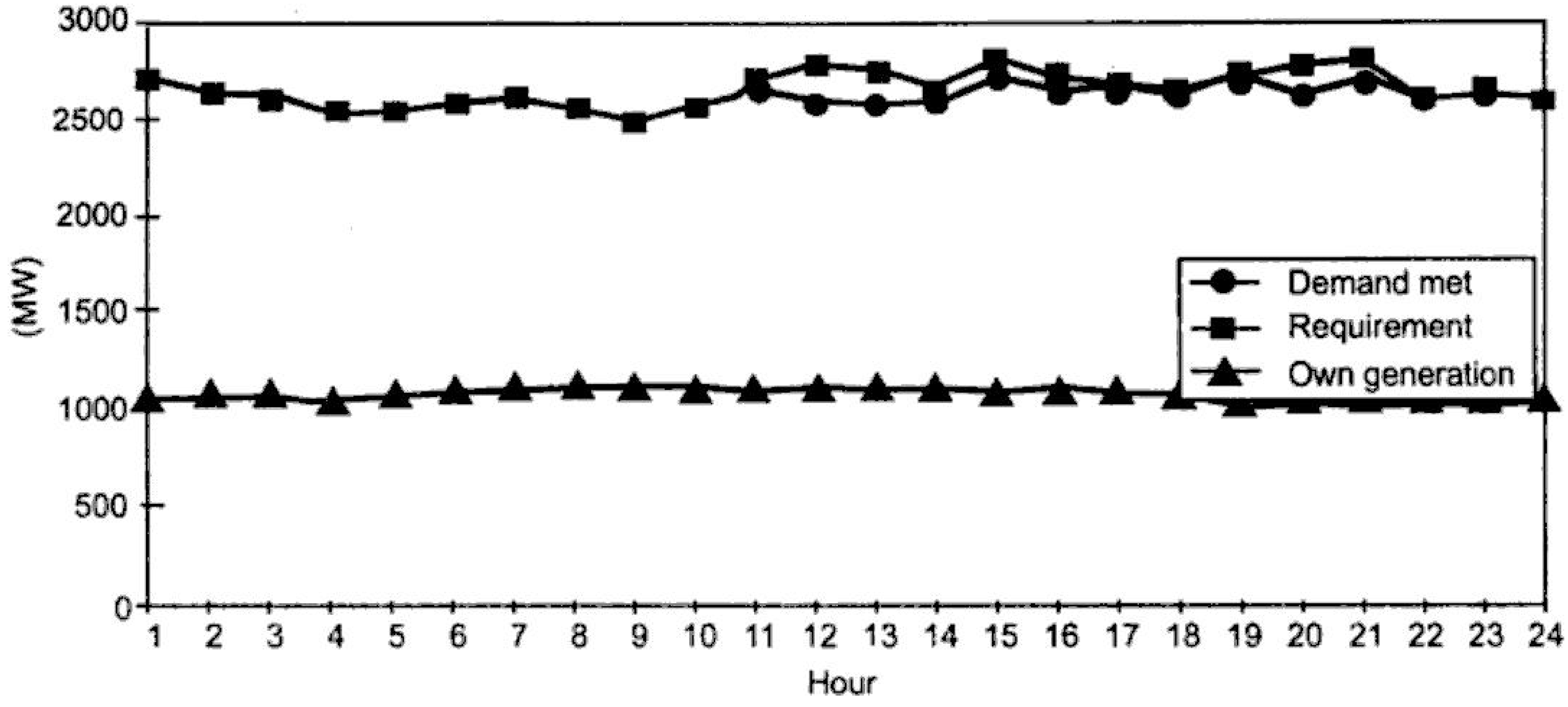


Fig. 1.25 Monsoon season

For each category of load, the load curve may be plotted. The summation of all these points gives the total load curve.

The maximum demand on the generating station can be obtained from the load curve for the given period. The maximum demand is nothing but the maximum load on the station during a given period. The peak load obtained from the load curve is not the maximum demand. The maximum demand is the largest average load on the station for specified period. If the load readings are monitored continuously then the greatest load will represent instantaneous maximum demand.

If it is stated that the maximum demand is x kW, then it is meaningless unless it is specified by the time duration. The accuracy of this will dependent on how accurately the readings are obtained from load curves, scale of the curve and the number of ordinates taken within the specified period. The capacity of generating units can be decided from this information.

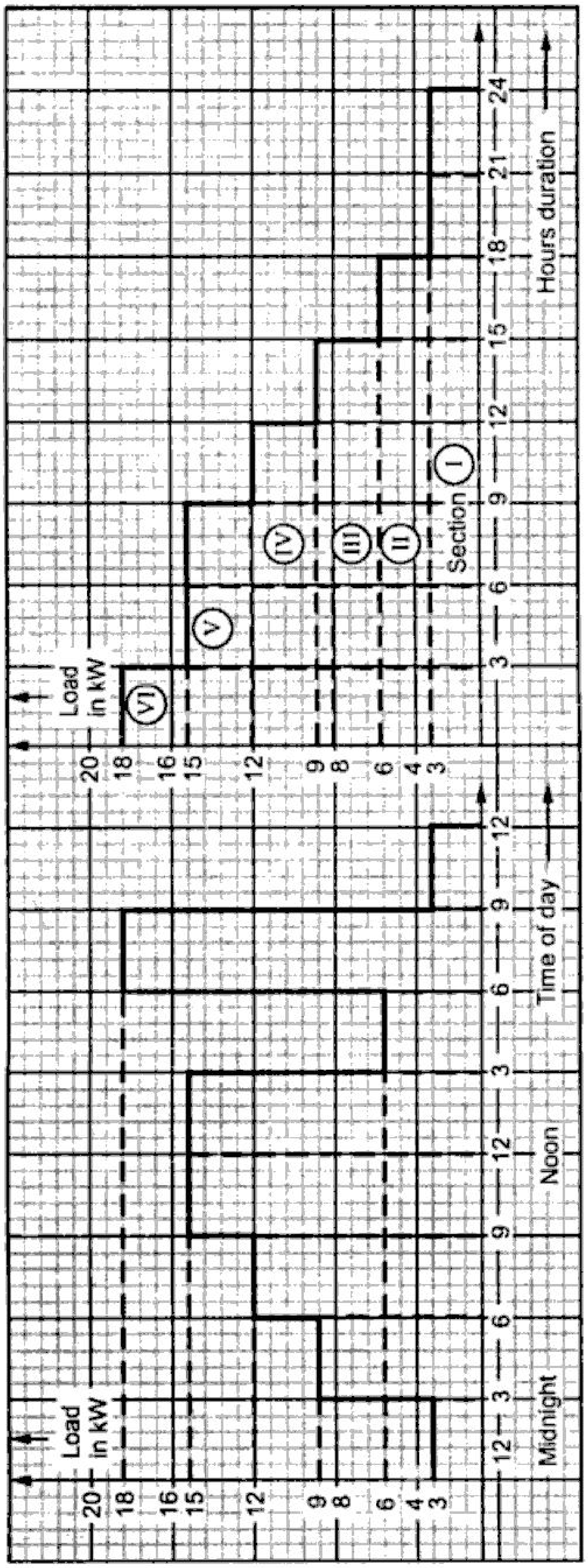
1.23 Load Duration Curve

The curve obtained by arranging the load elements of a load curve in order of decreasing magnitudes is called load duration curve. No extra data or information is required for plotting this curve as it can be plotted with the same data as that for load curve.

The ordinates from the load curve arranged in order of decreasing magnitudes. The peak load is shown to the left while the decreasing loads are arranged to the right in the descending order. It is quite obvious that the area under load curve and load duration curve is same.

The area under load duration curve indicates the total number of units that are consumed in that time. The load factor of the station can be determined from this. It also suggests the division of load between various generating units (alternators) of the plant to operate them near their maximum efficiency points.

Fig. 1.26 (a) shows the daily load curve. The corresponding daily load duration curve is shown in the Fig. 1.26 (b).



(a) Load curve

(b) Load duration curve

Fig. 1.26

The load elements of 3 kW, 6 kW, 9 kW, 12 kW, 15 kW and 18 kW are arranged in decreasing order for the respective time duration on the load duration curve. The total load supplied can be divided into various sections (sections I to VI in this case). Let us say that there are 6 alternators corresponding to these sections.

The alternator which supplies load of 3 kW will be in operation almost continuously with high load factor. When the load is increased to 6 kW, then the second alternator will be put in service which will have comparatively low load factor. Likewise the alternators will be put in operation with decreasing load factors.

The important points that can be observed from the load duration curve are summarized as given below.

1. The data obtained from load duration curve is in more presentable form as it shows the number of hours for which the load was present on the station.
2. It gives number of units generated after finding the area under that curve.
3. The load duration curve can be plotted for entire year by considering time period of 8760 hours (hours of a year 24 hrours × 365 days = 8760 hrours) on X-axis. Thus the variation and corresponding distribution of load can be obtained.

1.24 Integrated Load Duration Curve

A plot of number of units generated (kWh) for a given demand (kW) is called integrated load duration curve on Y-axis, load demand in kW or MW is plotted while on X-axis corresponding number of units generated are obtained. Such a curve corresponding to load duration curve shown in Fig. 1.27.

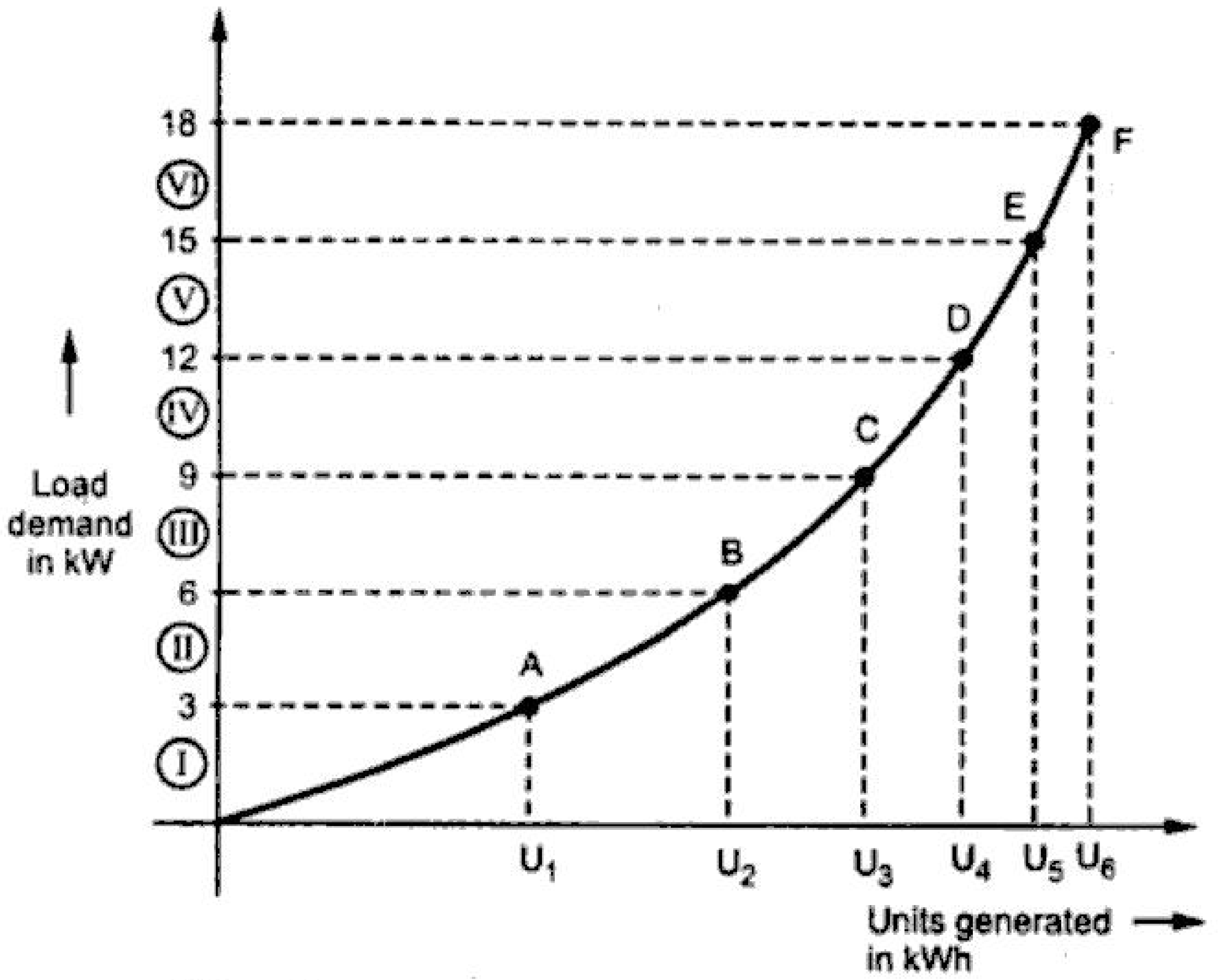


Fig. 1.27 Integrated load duration curve

This curve is obtained from load duration curve. Let the load demand be 3 kW from the load duration curve in section I. The number of units generated corresponding to this demand will be area under section I which is shown as U_1 in integrated load duration curve. Similarly the other points are also obtained to get a total curve.

The number of units consumed by a load upto a particular time of a day can also be shown on a curve which is called as mass curve.

1.25 Selection of Size and Number of Generating Units

For deciding the size and number of generator units, firstly the load curve and other relevant parameter and factors from the load curve are to be determined. In order to calculate the size of the units, the station auxiliary load and the line losses should be considered. It can be approximately taken as 20 % of the consumer load.

The minimum number of units will be one. But there are drawbacks in selecting a single unit to meet maximum demand are as given below

1. The rating of the unit should be such as to meet the maximum demand. But as the load on station is variable and load factor is less than 100 % there is considerable time during which the load will be much less than maximum demand. During this period the unit may run at half load or even practically at no load. Hence it is not running all time to give maximum efficiency. It is also not economical to run the set at light load as fuel consumption will be more.
2. With only one unit, reliability of operation is reduced significantly eventhough power can be obtained at cheaper rate. If the same unit is under repair or maintenance then continuity of supply is lost unless there is second unit present which may increase capital cost. Thus in the environment of variable load where reliability of supply is important it is neither practical nor economical to use a single unit.

The number of units are to be selected in such a way as to fit in the load curve as closely as possible. Then each unit can be made to operate in such a way that it runs almost at full load or at a load which gives maximum efficiency. The reserve capacity required in this case will only be a single largest unit which would be much smaller than the maximum reserve capacity that would be required with a single unit case. Thus plant capacity and plant use factor is improved. But there are following shortcomings of this system.

1. With increase in number of units, the floor area required is more and so corresponding cost is also more.
2. The cost for maintenance also increases.
3. With large number of units, there will be frequent starting, stopping and parallel operation of units which needs increased persons for handling the equipments.
4. Capital cost for large number of units is more than that of same capacity with smaller number of units of large size.

Thus selection of number of units is a critical task as a single unit as well as large number of smaller units would be unreliable and uneconomical. Thus a compromise is made in selection of these units. The best compromise between plant capacity and plant capacity factor also gives choice for selecting the units.

The following points should be considered for selection of units for various stations.

i) The load factor of the units should be high.

ii) The minimum number of units selected should be two.

iii) The plant must have some reserve capacity under abnormal conditions.

iv) With two units selected, both must be able to supply maximum demand or load.

v) The future demand and expansion should also be considered as the load on the station always increases.

vi) For large number of small units, the space and capital cost required is more.

As far as possible, the units of equal capacities are selected which will have following advantages.

i) The parts can be interchanged.

ii) The maintenance will be easier.

iii) The working time of each plant is suitably regulated.

iv) The spare parts required to be stored are less.

In summary, the selected units should work at high efficiency as the capital cost and running cost will then be minimum.

1.26 Interconnection of Power Stations

The connection of various generating stations in parallel is called interconnection of power stations or also called interconnected grid system. There are several advantages of this grid system and the cost associated with the interconnection through extra comparable to the benefits obtained from it.

Before studying the advantages of this grid system let us consider the concept of base load and peak load.

We have seen that the load on the power station is never constant but keeps on changing with time. This load can be subdivided into two parts viz. i) Base load ii) Peak load.

The unvarying load or fixed load which occurs almost whole day on the plant is called base load. The various peak demands of the load over and above base load of the power plant is called peak load.

Consider the load curve with base load and peak load shown in the Fig. 1.28

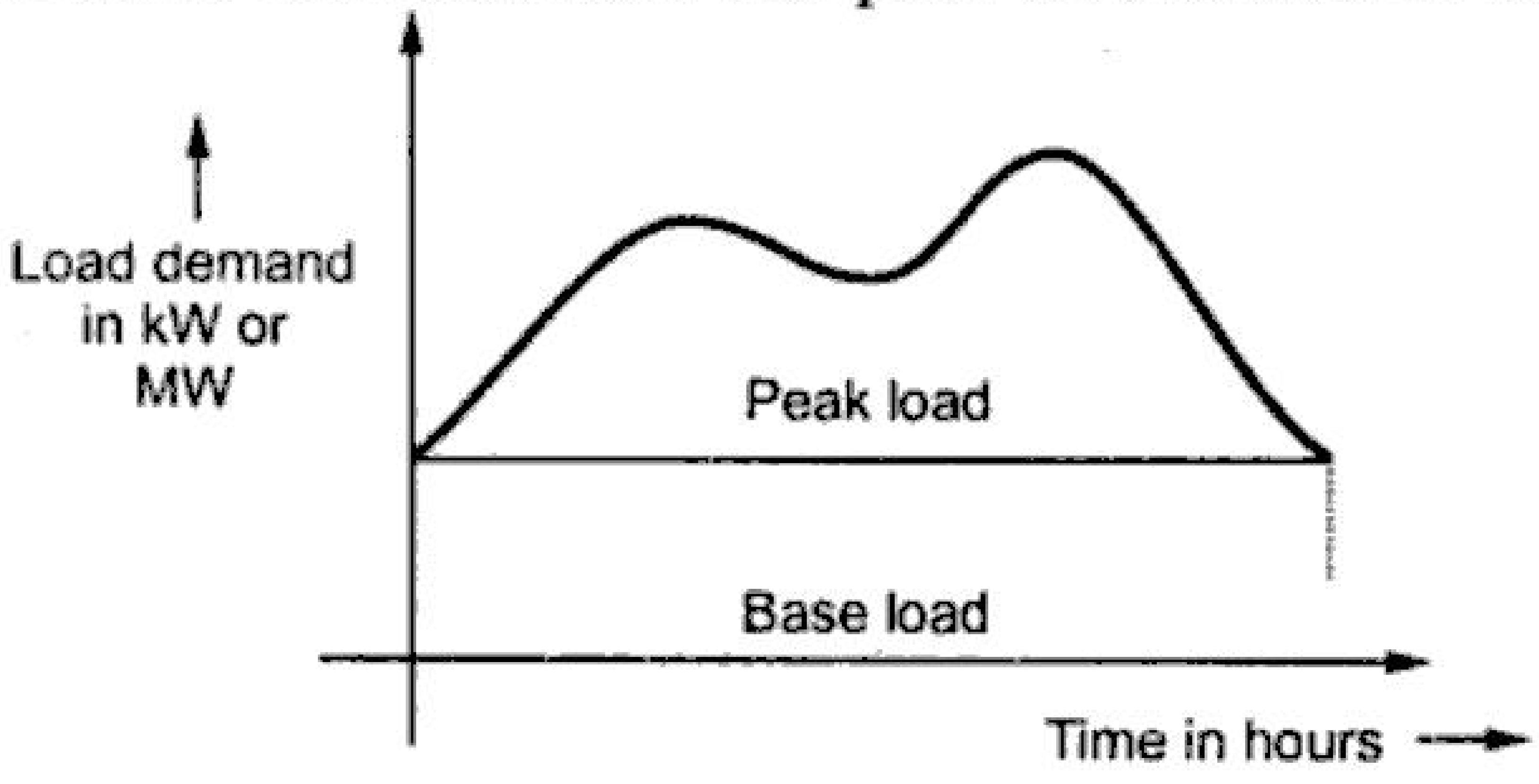


Fig. 1.28

Now if such load curve is to be met by a single unit then its installed capacity should be equal to peak load demand or even more. As peak load occurs for short duration such solution is not economical that we have seen earlier. The other way is to divide the load into base load and peak load. Thus by interconnection of various power stations of different types, some stations will supply base load while some other stations will supply peak load. Thus the co-ordination of operation of different power stations is essential which is shown in the Fig. 1.29.

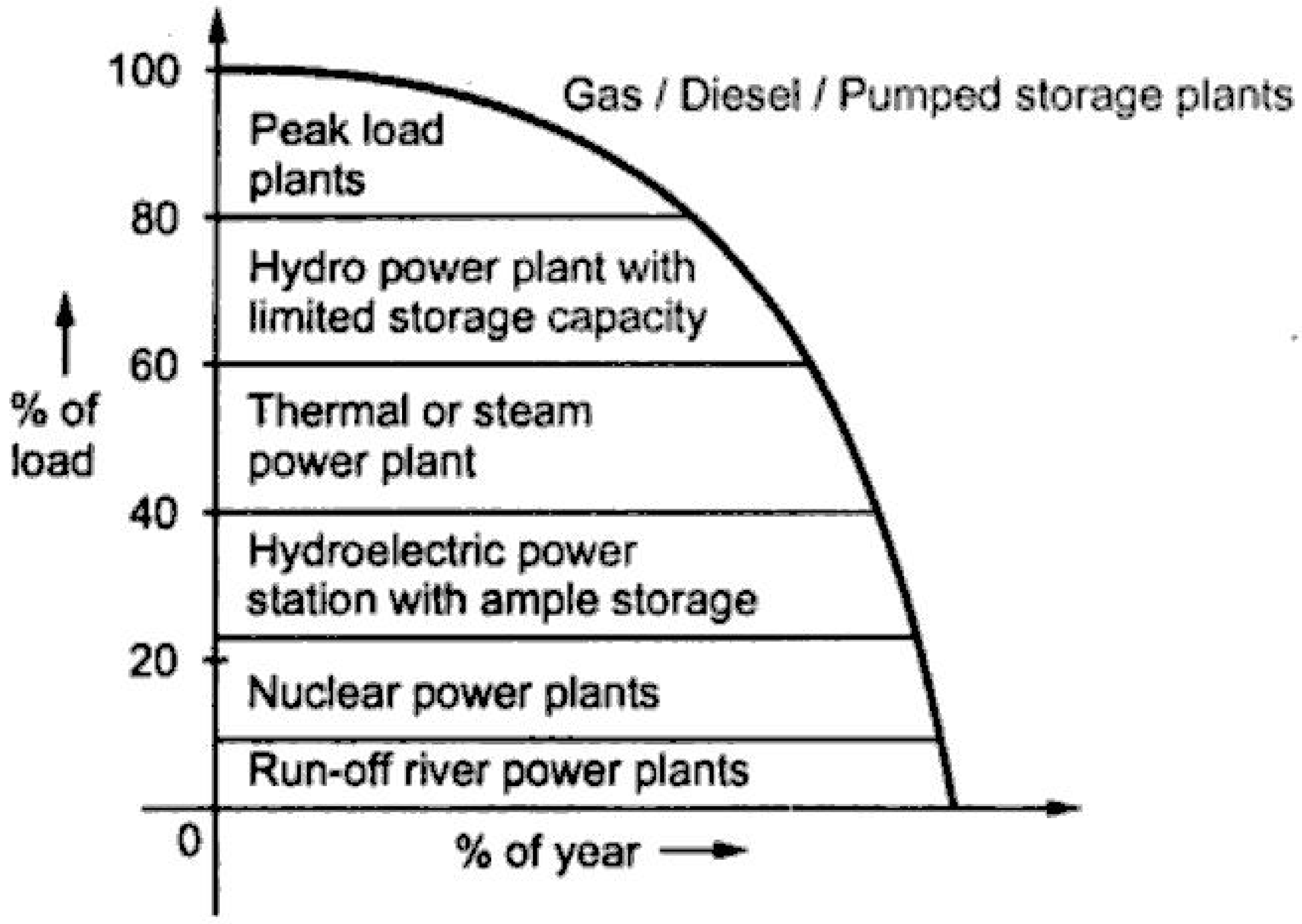

100
80
60
40
20
0
% of load
% of year
Peak load plants
Gas / Diesel / Pumped storage plants
Hydro power plant with limited storage capacity
Thermal or steam power plant
Hydroelectric power station with ample storage
Nuclear power plants
Run-off river power plants

Fig. 1.29

The power plant which are working as base load should be capable of working continuously for long periods. It should have low operating cost. Its repair should be economical and speedy.

The peak load power plants should be capable of quick start, fast synchronization, quick taking of load and fast response to load variations.

The hydro power plant serves as base load or peak load efficiently. They are normally employed as base load plants as their capital cost is high. When water is not abundantly available then the hydro power plant works as peak load.

The cost of generation per unit steam power plant is minimum. Hence it can be employed as base load. Nuclear power plants are also employed as base load. Diesel, gas and pumped storage plants are used as peak load plants.

The advantages of interconnected system are as given below.

1) With interconnected grid system the peak load can be exchanged between the generating stations. From load curve if there is peak load demand which is more than rated capacity of the plant then the excess load can be shared by other interconnected stations.

2) It is possible to use the older and inefficient plants with grid system for short duration to supply peak demands. These units may not operate independently but with grid system they can sustain peak loads. Thus older plants can be effectively used with this system.
3) With interconnected grid system the economical operation of the plant is possible. The total load is arranged in such a way that more efficient plants can be used as base load stations which can work continuously throughout the year at high load factor. The less efficient plants can be made to operate as peak load plants. Also larger generator units can be employed to reduce capital cost per kW.
4) Various interconnected plants have their load curves different due to which maximum demand on the system is reduced as compared to sum of individual maximum demands on various stations. Thus the effective capacity of the system increased as their is improvement in diversity factor.
5) It can be seen that the load curves of the two different stations are not identical. In worst case conditions the peak loads may occur at a time differing by few minutes. Thus the maximum demands on individual stations are not occurring simultaneously, it is possible to work with lesser installed capacity with interconnected grid system.
6) In abnormal conditions every station should have reserve standby unit to be put in operation. With grid system the reserve capacity is reduced which increases efficiency of the system.
7) The reliability and continuity of the supply is improved with interconnected grid system. With faulty condition occurring in any one station, the supply can be maintained with the help of other stations.

1.27 Cost of Electrical Energy

The cost associated with the electrical energy can be divided into three parts

i) Fixed cost

ii) Semi fixed cost

iii) Running cost.

1.27.1 Fixed Cost

This is the cost which is independent of the maximum demand and the units which are generated. It is the cost which must be spent for purchase of assets such as land and equipments required for plant. It also consists of annual cost of central organization, interest on capital cost of land and salaries of high officials. Irrespective of whether plant is generating energy or unit, whether the maximum demand is low or high, the annual expenditure of central organization and salaries of high officials is fixed. The capital investment on land and rate of interest is also fixed.

1.27.2 Semi Fixed Cost

The cost which is not dependent on the number of units generated but depends on maximum demand is called semi fixed cost. It is proportional to maximum demand and is due to annual interest and depreciation on capital investment of buildings and equipments, different types of taxes, insurance charges along with salaries of management and clerical staff. The size and the cost associated with installation of plant is determined from the maximum demand. With increase in maximum demand, the size and cost of installation of plant is greater. With increase in size, the taxes and clearical staff will also be large.

1.27.3 Operating or Running Cost

It is defined as the cost which is dependent on the number of units generated. It consists of following costs.

i) Fuel cost

ii) Cost associated with lubricating oil and water

iii) Maintenance and repairing cost of the equipment in generation, transmission and distribution sections.

iv) The salaries of operating and supervising staff.

All these costs are dependent on output energy from the plant. The running cost is always proportional to number of units generated by the station. High running cost indicates that the number of units generated by station is high.

Examples with Solutions

➠ **Example 1.1 :** *A generating station has a connected load of 40 MW and a maximum demand of 20 MW; the units generated being 60 × 10^6. Calculate i) The demand factor ii) Load factor.*

Solution : Units generated = 60×10^6

$$\text{Connected load} = 40 \text{ MW}$$

$$\text{Maximum demand} = 20 \text{ MW} = 20000 \text{ kW}$$

$$\text{Demand factor} = \frac{\text{Maximum demand}}{\text{Connected load}} = \frac{20}{40} = \mathbf{0.5}$$

$$\text{Average demand} = \frac{\text{Units generated / Annum}}{\text{Hours in a year}}$$

$$= \frac{60 \times 10^6}{8760} = 6849.31 \text{ kW}$$

$$\therefore \quad \text{Load factor} = \frac{\text{Average demand}}{\text{Maximum demand}} \times 100$$

$$= \frac{6849.31}{20000} \times 100$$

$$\therefore \quad \text{Load factor} = \mathbf{34.24\ \%}$$

Example 1.2 : *A generating station has a maximum demand of 400 MW. The annual load factor is 60 % and capacity factor is 45 %. Find the reserve capacity of the plant.*

Solution : Maximum demand = 400 MW

$$\text{Annual load factor} = 60\ \%$$

$$\text{Capacity factor} = 45\ \%$$

$$\text{Annual load factor} = \frac{\text{Units generated in T Hours}}{\text{Maximum demand} \times \text{Hours / year}}$$

$$\therefore \quad \text{Units generated} = 0.6 \times 400 \times 8760 = 2.10 \times 10^6 \text{ MWh}$$

$$\text{Capacity factor} = \frac{\text{Actual energy produced}}{\text{Maximum energy that could have been produced}}$$

$$= \frac{\text{Actual energy produced}}{\text{Plant capacity} \times \text{Hours in year}}$$

$$\therefore \quad \text{Plant capacity} = \frac{2.10 \times 10^6}{0.45 \times 8760} = 533.33 \text{ MW}$$

$$\text{Reserve capacity} = \text{Plant capacity} - \text{Maximum demand}$$

$$= 533.33 - 400$$

$$= \mathbf{133.33\ MW}$$

Example 1.3 : *A 100 MW power station delivers 100 MW for 2 hours, 50 MW for 8 hours and is shut down for the rest of each day. It is also shut down for maintenance for 60 days each year. Calculate the annual load factor.*

Solution : Load on power station = 100 MW for 2 hours

and 50 MW for 8 hours

$$\text{Maximum demand} = 100 \text{ MW}$$

$$\text{Total days of operation} = 365 - 60 = 305$$

$$\text{Energy generated per day} = 100 \times 2 + 50 \times 8$$

$$= 600 \text{ MWh}$$

$$\text{Total energy generated in year} = 600 \times 305$$

$$= 183000 \text{ MWh}$$

$$\text{Annual load factor} = \frac{\text{Total energy generated}}{\text{Maximum demand} \times \text{Hours of operation of year}} \times 100$$

$$= \frac{183000}{100 \times 305 \times 24} \times 100$$

$\therefore$ Annual load factor = **25 %**

Example 1.4 : *A generating station supplies the following loads 15000 kW, 12000 kW, 8500 kW, 6000 kW, 450 kW. The station has a maximum demand of 22000 kW. The annual load factor of the station is 48 %. Calculate i) The number of units supplied annually ii) The diversity factor iii) The demand factor.*

Solution : Total load = 15000 + 12000 + 8500 + 6000 + 450 = **41950 kW**

$$\text{Maximum demand} = 22000 \text{ kW}$$

$$\text{Annual load factor} = 48\ \% = 0.48$$

$$\text{Demand factor} = \frac{\text{Maximum demand}}{\text{Connected load}} \times 100$$

$$= \frac{22000}{41950} \times 100$$

$$= \mathbf{52.44\ \%}$$

$$\text{Diversity factor} = \frac{\text{Sum of individual maximum demand}}{\text{Maximum demand}}$$

$$= \frac{41950}{22000} = \mathbf{1.9}$$

$$\text{Annual load factor} = \frac{\text{Units generated in year}}{\text{Maximum demand} \times \text{Hours of opearation in year}} \times 100$$

$$\therefore \quad \text{Units generated in year} = 0.48 \times 22000 \times 8760$$

$$= \mathbf{925.056 \times 10^5 \text{ kWh}}$$

Example 1.5 : *The yearly load duration curve of a certain power station can be approximated as a straight line. The maximum and minimum loads being 80 MW and 4 MW respectively. To meet this load, three turbine generator units, two rated at 20 MW each and one at 10 MW are installed. Determine i) Installed capacity ii) Plant factor iii) kWh output per year iv) Load factor.*

Solution :

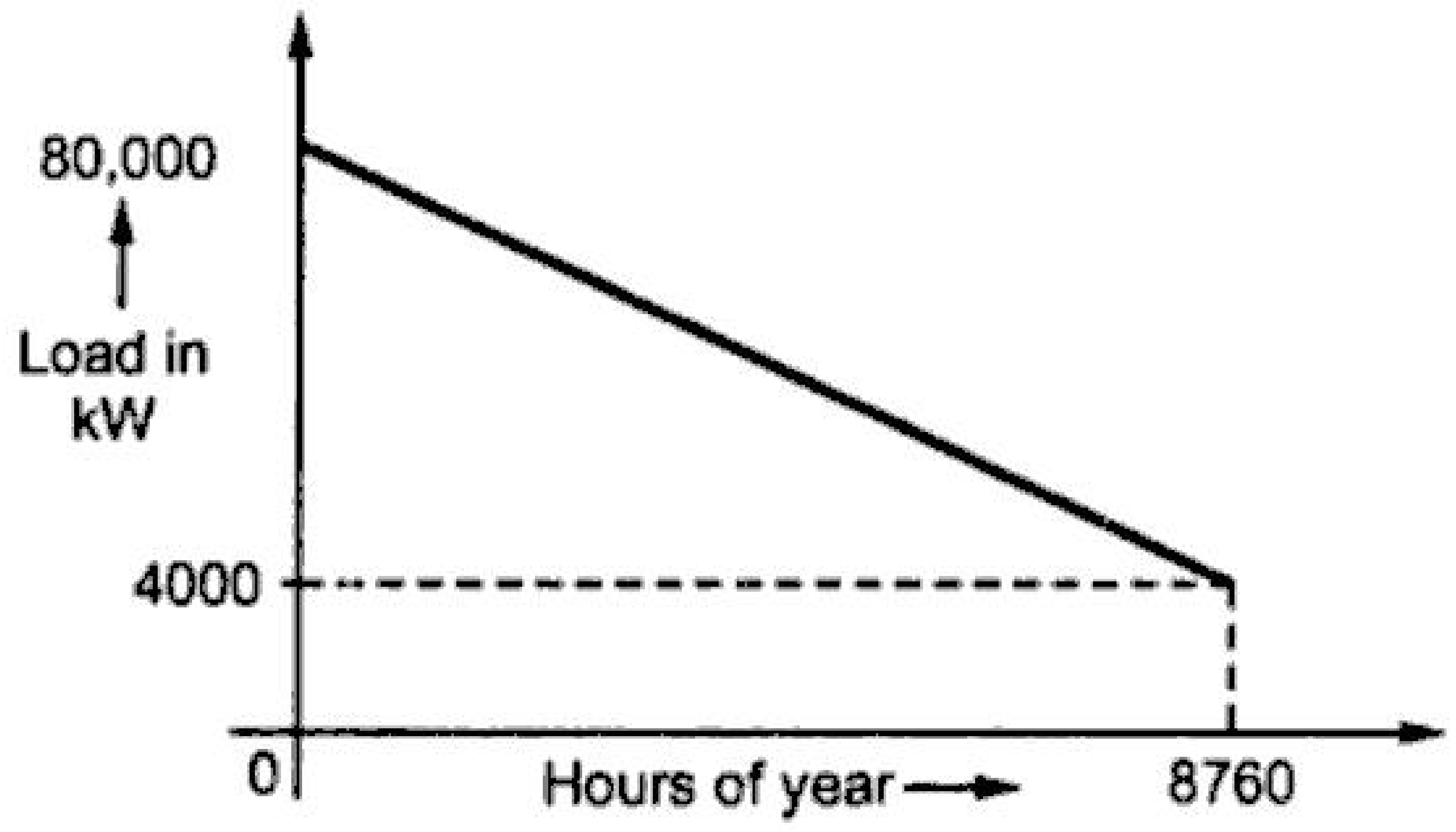


Fig. 1.30

$$\text{Installed capacity} = 20 + 20 + 10 = \mathbf{50\ MW}$$

$$\text{Average demand} = \frac{1}{2}[4+80] = 24 \text{ MW}$$

$$\therefore \quad \text{Plant factor} = \frac{\text{Average demand}}{\text{Plant installed capacity}} = \frac{24}{50} = \mathbf{0.48}$$

$$\text{Units generated/annum} = \text{Area under load duration curve}$$

$$= \frac{1}{2}[80000+4000] \times 8760$$

$$= \mathbf{3.67 \times 10^8\ kWh}$$

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum load}} = \frac{24}{80} \times 100$$

$$\therefore \quad \text{Load factor} = \mathbf{30\ \%}$$

Example 1.6 : *A generating station has a maximum demand of 20 MW, a load factor of 60 %, a plant capacity factor of 48 % and plant use factor of 80 %. Find*

i) The daily energy produced.

ii) The reserve capacity of the plant.

iii) The maximum energy that could be produced daily if the plant was running all the time.

iv) The maximum energy that could be produced daily if the plant was running fully loaded and operating as per schedule.

Solution : Maximum demand = 20 MW

$$\text{Load factor} = 60\ \% = 0.6$$

$$\text{Plant capacity factor} = 48\ \% = 0.48$$

$$\text{Plant use factor} = 80\ \% = 0.8$$

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}} \times 100$$

$$\therefore \quad 0.6 = \frac{\text{Average load}}{20}$$

$$\therefore \quad \text{Average load} = 12 \text{ MW}$$

$$\text{Energy produced per day} = 12 \times 24 = 288 \text{ MWh}$$

$$= \mathbf{288 \times 10^3 \ kWh}$$

$$\text{Plant capacity factor} = \frac{\text{Annual kWh output}}{\text{Plant capacity} \times 8760}$$

$$= \frac{\text{Average demand}}{\text{Plant capacity}}$$

$$\therefore \quad \text{Plant capacity} = \frac{12}{0.48} = 25 \text{ MW}$$

$$\therefore \quad \text{Reserve capacity} = \text{Plant capacity} \times \text{Maximum demand}$$

$$= 25 - 20$$

$$= \mathbf{5 \ MW}$$

$$\text{Capacity factor} = \frac{\text{Annual energy produced}}{\text{Maximum energy that would have been produced}}$$

$$\text{Maximum energy produced} = \frac{288 \text{ MWh}}{0.48} = \mathbf{600 \ MWh}$$

$$\text{Plant use factor} = \frac{\text{Station output}}{\text{Plant capacity} \times \text{Hours of use}}$$

$$= \frac{\text{Station output}}{\text{Maximum energy produced if plant is operated as per schedule}}$$

$$\therefore \text{Maximum energy produced if plant is operated as per schedule} = \frac{288}{0.8}$$

$$= \mathbf{360 \ MWh}$$

➠ **Example 1.7 :** *The supply system has following types of loads .*

Type of load	M.D. (kW)	L.F. (%)	Diversity factor	Overall diversity
Domestic	2000	25	1.2	1.35
Commercial	5000	30	1.15	
Idustrial	8000	75	1.25	

What are connected load of each category if the demand factor for domestic, commercial and idustrial loads are 50, 60 and 80 percent respectively ? Find i) Maximum demand ii) Daily energy consumption iii) Load factor.

Solution : Sum of individual maximum demands = 2000 + 5000 + 8000 = 15000 kW

Overall diversity factor = 1.35

∴ Maximum demand can be calculated as,

$$\text{Diversity factor} = \frac{\text{Sum of individual maximum demands}}{\text{Maximum demand}}$$

∴ Maximum demand = 1.35 × 15000 = **20250 kW**

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}}$$

∴ Average load = Load factor × Maximum demand

For domestic load,

Average demand = 0.25 × 2000 = 500 kW

For commercial load,

Average demand = 0.30 × 5000 = 1500 kW

For industrial load,

Average demand = 0.75 × 8000 = 6000 kW

∴ Energy consumption per day = (5000 + 1500 + 6000) × 24

$= \mathbf{3 \times 10^5\ kWh}$

$$\text{Load factor of supply system} = \frac{\text{Daily energy consumption}}{\text{Maximum demand} \times 24}$$

$$= \frac{\text{Total average demand}}{\text{Maximum demand}} = \frac{12500}{20250} \times 100$$

= **61.72 % or 0.6172**

Each type of load has its own diversity factor among its consumers.

Maximum demand for domestic load = Maximum demand × Diversity factor

= 2000 × 1.2 = **2400 kW**

$$\therefore \quad \text{Demand factor for domestic load} = \frac{\text{Maximum demand}}{\text{Connected load}}$$

$$\therefore \quad \text{Connected load for domestic load} = \frac{2400}{0.5} = \mathbf{4800\ kW}$$

Maximum demand for commercial load = Maximum demand × Diversity factor

$= 5000 \times 1.15 = \mathbf{5750\ kW}$

$\therefore$ Demand factor for commercial load $= \dfrac{\text{Maximum demand}}{\text{Connected load}}$

$\therefore$ Connected load $= \dfrac{5750}{0.6}$

$\therefore$ Commercial connected load $= \mathbf{9583.33\ kW}$

Maximum demand for industrial load $=$ Maximum demand $\times$ Diversity factor

$= 8000 \times 1.25 = \mathbf{10000\ kW}$

$\therefore$ Demand factor for industrial load $= \dfrac{\text{Maximum demand}}{\text{Connected load}}$

$\therefore$ Connected load $= \dfrac{10000}{0.8}$

$\therefore$ Industrial connected load $= \mathbf{12500\ kW}$

Example 1.8 : *A generating station has the following daily load cycle.*

Time (Hours)	0 - 6	6 - 10	10 - 12	12 - 16	16 - 20	20 - 24
Load (MW)	20	25	30	25	35	20

Draw the load curve and find

i) Maximum demand *ii) Units generated per day*

iii) Average load *iv) Load factor*

Solution : The load curve is shown in the Fig. 1.31. (Refer Fig. 1.31 on next page). From the load curve it can be seen that maximum demand of 35 MW during the period 16-20 hours.

$\therefore$ Maximum demand $= \mathbf{35\ MW}$

Units generated /day $=$ Area under load curve

$= [20\times 6+25\times 4+30\times 2+25\times 4+35\times 4+20\times 4]$

$= [120+100+60+100+140+80]$ MWh

$= \mathbf{600 \times 10^3\ kWh}$

Average load $= \dfrac{\text{Units generated / Day}}{\text{24 hours}} = \dfrac{600\times 10^3}{24}$

$= 25000$ kW

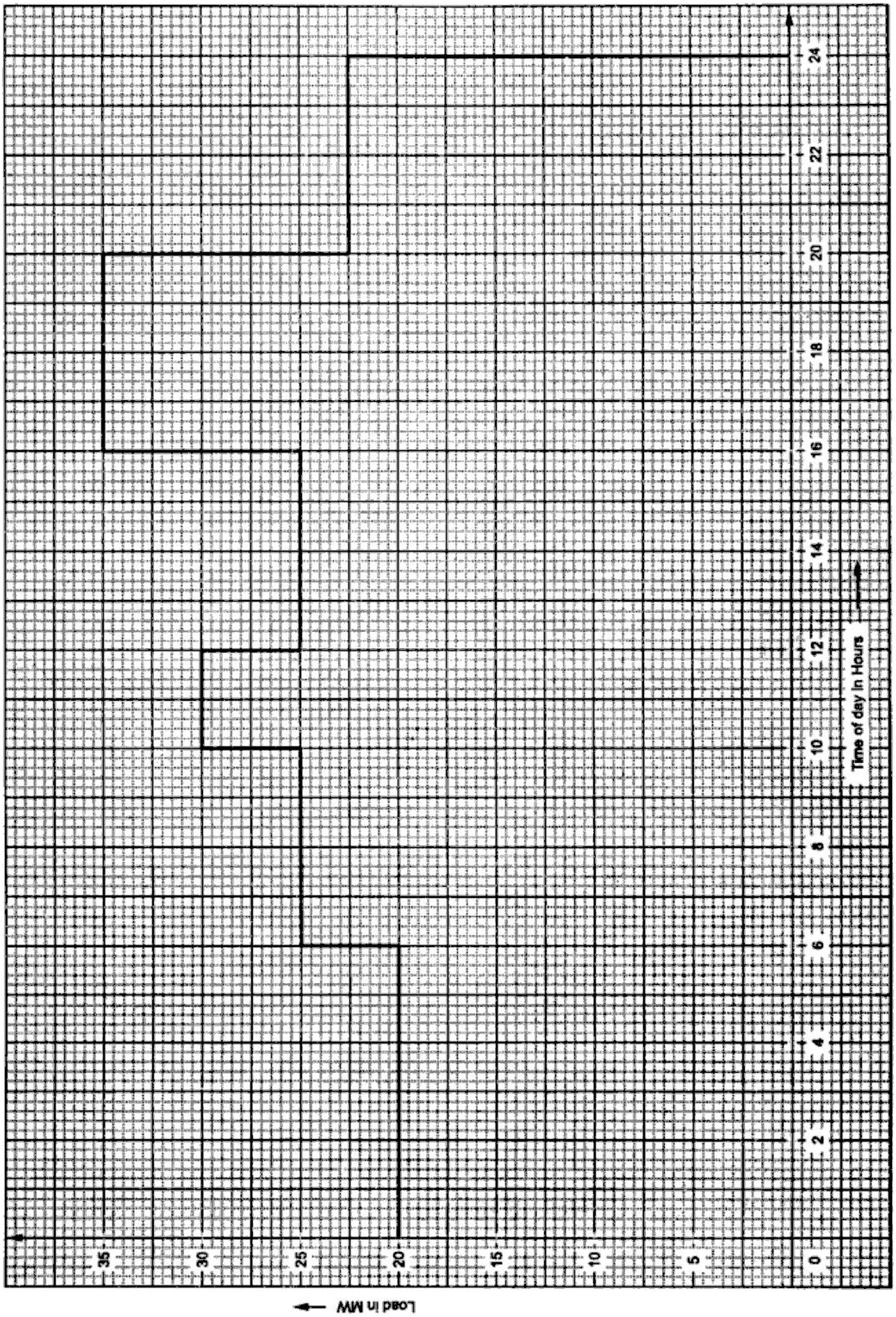


Fig. 1.31 Daily load curve

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}} = \frac{25000}{35000}\times 100$$

$$\therefore \quad \text{Load factor} = \mathbf{71.42\ \%}$$

Example 1.9 : *An electric supply undertaking has to cater to demands of 4 consumers A, B, C, D each having a M.D. of 5 kW. Variation of loads for these consumers is given below.*

Consumer A

From midnight to 7 a.m.	*200 W*
From 7 a.m. to 7 p.m.	*1500 W*
From 7 p.m. to 9 p.m.	*5000 W*
From 9 p.m. to midnight	*800 W*

Consumer B

From midnight to 9 a.m.	*600 W*
From 9 a.m. to 12 noon	*2500 W*
From 12 noon to 5 p.m.	*800 W*
From 5 p.m. to 6 p.m.	*5000 W*
From 6 p.m. to midnight	*4000 W*

Consumer C

From midnight to 6 a.m.	*400 W*
From 6 a.m. to 12 noon	*1600 W*
From 12 noon to 2 p.m.	*5000 W*
From 2 p.m. to 7 p.m.	*600 W*
From 7 p.m. to 11 p.m.	*3600 W*
From 11 p.m. to midnight	*600 W*

Consumer D

From midnight to 8 a.m.	*800 W*
From 8 a.m. to 1 p.m.	*5000 W*
From 1 p.m. to 2 p.m.	*800 W*
From 2 p.m. to 5 p.m	*5000 W*
From 5 p.m. to midnight	*800 W*

Draw separate load curves for each consumer and system load curve. Find maximum demand on the system. Also calculate i) Load factor ii) Diversity factor for supply system.

Solution : The individual load curve for each type of consumer is shown in the Fig. 1.32. (Refer Fig. 1.32 on next page).

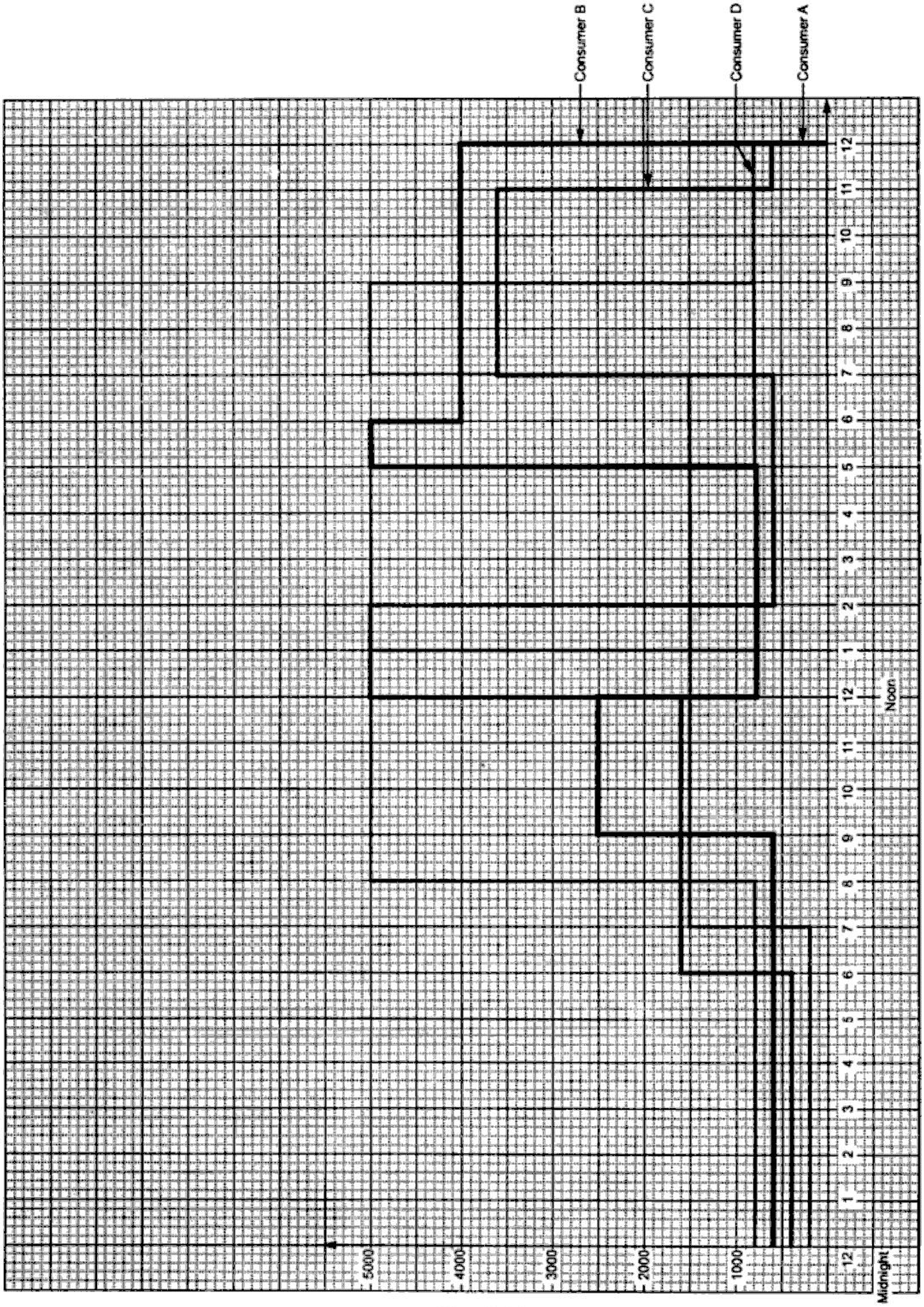

Consumer B
Consumer C
Consumer D
Consumer A
5000
4000
3000
2000
1000
12
1
2
3
4
5
6
7
8
9
10
11
12
Noon
1
2
3
4
5
6
7
8
9
10
11
12
Midnight

Fig. 1.32

The system load curve can be plotted by summation of load demands of these consumers during various hours of day.

Consider a time duration of 1 hour and load demands of these consumers.

Consumer	Midnight 12-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11
A	200	200	200	200	200	200	200	1500	1500	1500	1500
B	600	600	600	600	600	600	600	600	600	2500	2500
C	400	400	400	400	400	400	1600	1600	1600	1600	1600
D	800	800	800	800	800	800	800	800	5000	5000	5000
Total (W)	2000	2000	2000	2000	2000	2000	3200	4500	8700	10600	10600

Consumer	Noon 11-12	12-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12
A	1500	1500	1500	1500	1500	1500	1500	1500	5000	5000	800	800	800
B	2500	800	800	800	800	800	5000	4000	4000	4000	4000	4000	4000
C	1600	5000	5000	600	600	600	600	600	3600	3600	3600	3600	600
D	5000	5000	800	5000	5000	5000	800	800	800	800	800	800	800
Total (W)	10600	12300	8100	7900	7900	7900	7900	6900	13400	13400	9200	9200	6200

The system load curve is plotted by considering above readings as shown in the Fig. 1.33. Refer Fig. 1.33 on next page.

$$\text{Units generated per day} = (2000\times 6)+3200+4500+8700+(3\times 10600)$$

$$+12300+8100+(4\times 7900)+6900+(2\times 13400)+(2\times 9200)+(6200)$$

$$= 170{,}500 \text{ Whr}$$

$$\text{Load factor} = \frac{\text{Units generated per day}}{\text{Maximum demand}\times\text{Hours of day}}\times 100$$

$$= \frac{170500}{13400\times 24}\times 100$$

$$\therefore \quad \text{Load factor} = 53\ \%$$

$$\text{Diversity factor} = \frac{\text{Sum of individual maximum demands}}{\text{Maximum demand}}$$

$$= \frac{5000+5000+5000+5000}{13400} = \frac{20000}{13400} = 1.43$$

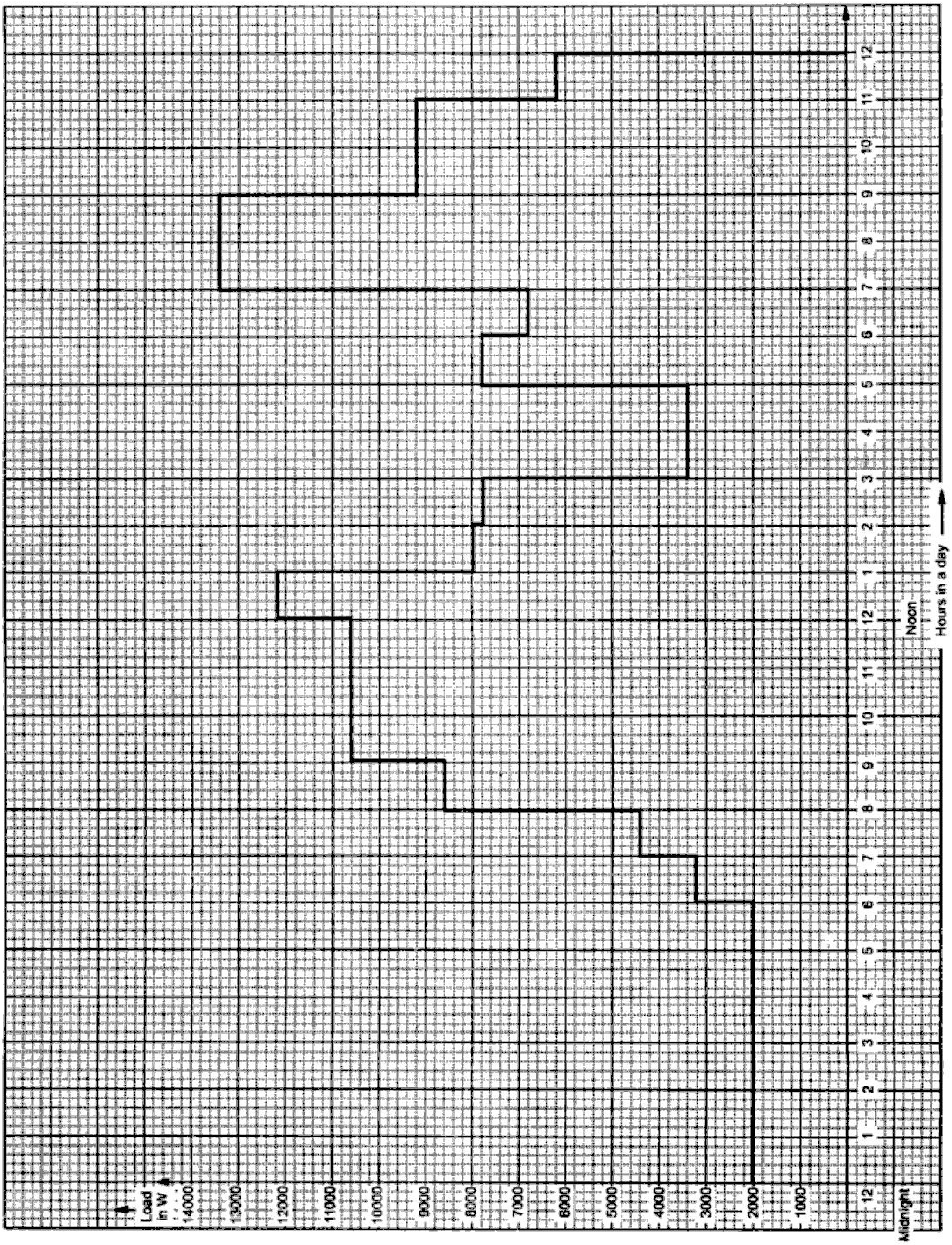


Fig. 1.33 Resultant load curve of system

Example 1.10 : *The load on a power plant for a particular day is as given below.*

Time	12-4 a.m.	4 a.m. to 8 a.m.	8 a.m. to 6 p.m.	6 p.m. to 8 p.m.
Load(kW)	15	35	70	80

Time	8 a.m. to 10 p.m.	10 p.m. to 12 p.m.
Load(kW)	90	15

Plot the load curve and load duration curve. Also plot the integrated load duration curve and mass curve. Find the load factor of the plant and the energy supplied by the plant in 24 hours.

Solution : From the given data the load curve is drawn which is as shown in the Fig. 1.34. Refer Fig. 1.34 on next page.

In order to draw load duration curve the ordinates of load are to be arranged in decreasing order. The greatest load on the left side, lesser load next to that and the lowest load on the right side. The load duration curve is as shown in the Fig. 1.34.

Load in kW	Duration of hours
90	2
80 and above	4
70 and above	14
35 and above	18
15 and above	24

Maximum demand on station = 90 kW

$$\text{Energy generated in 24 hours} = (90\times 2)+(80\times 2)+(70\times 10)+(35\times 4)+(15\times 6)$$

$$= 180 + 160 + 700 + 140 + 90$$

$$= 1270 \text{ kWh}$$

$$\text{Load factor} = \frac{\text{Energy generated per day}}{\text{Maximum demand}\times 24}\times 100$$

$$= \frac{1270}{90\times 24}\times 100$$

$$= \mathbf{58.79\ \%}$$

The integrated load duration curve is curve between demand in kW or MW and the total energy generated upto that demand. It is shown in the Fig. 1.34.

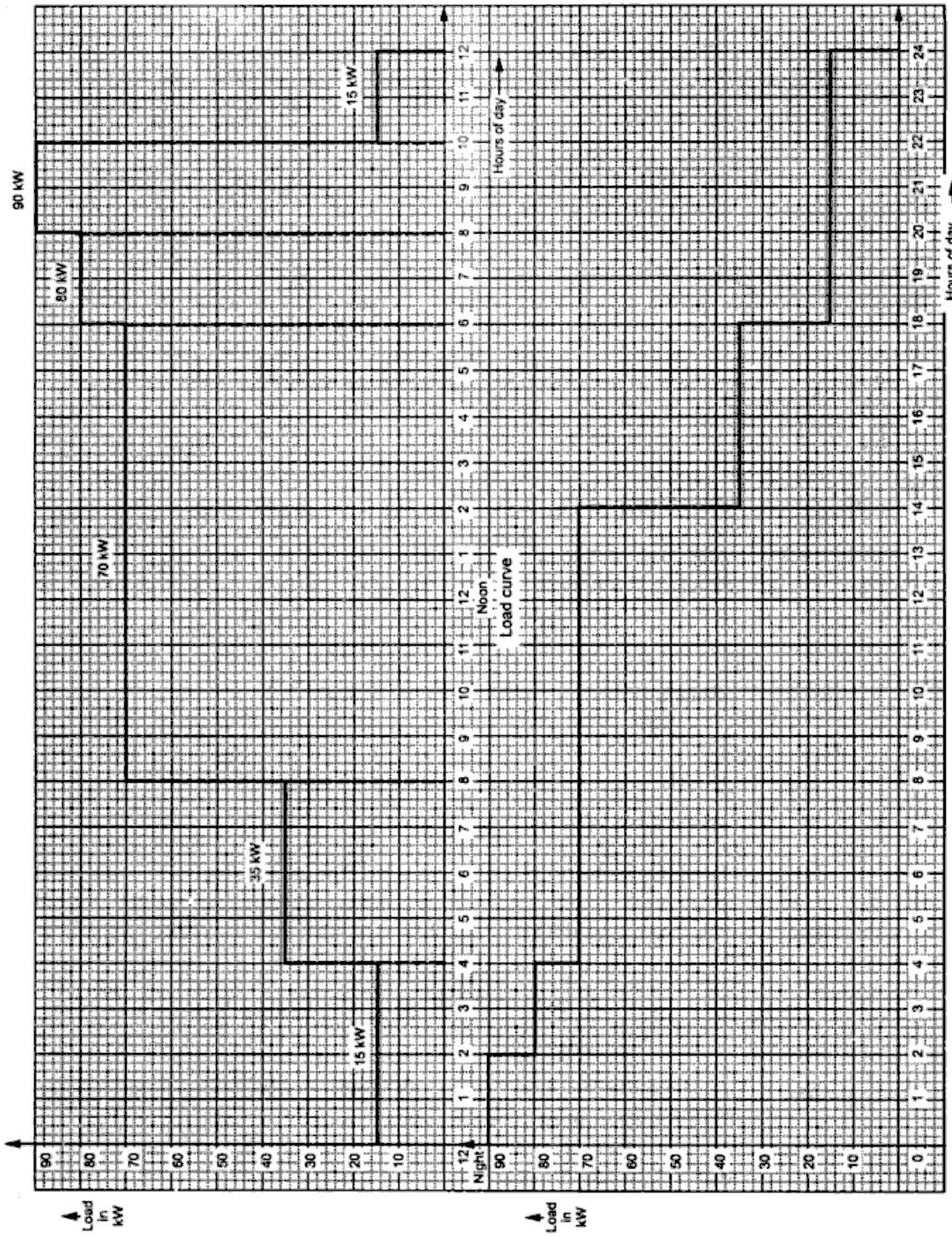

90 kW
80 kW
70 kW
35 kW
15 kW
15 kW
Load curve
Hours of day
Noon
Night
Load in kW
90
80
70
60
50
40
30
20
10
12
1
2
3
4
5
6
7
8
9
10
11
12
Load duration curve
Hours of day
0
13
14
15
16
17
18
19
20
21
22
23
24
Load in kW

Fig. 1.34

Load in kW	15	35	70	80	90
Energy generated (kWh)	15 × 24 = 360	360 + 20 × 18 = 720	720 + 35 × 14 = 1210	1210 + 10 × 4 = 1250	1250 + 10 × 2 = 1270

Mass curve is plotted between the energy generated upto particular time in a day. The energy generated upto different times of day are obtained from load curve as given below.

Time	0	4 a.m	8 a.m	6 p.m	8 p.m	10 p.m	12 p.m
Energy generated in kWh upto that time	0	15 × 4 = 60	60 + 35 × 4 = 200	200 + 10 × 70 = 900	900 + 2 × 80 = 1060	1060 + 2 × 90 = 1240	1240 + 2 × 15 = 1270

The mass curve is represented in Fig. 1.35. Refer Fig. 1.35 on next page.

➠ **Example 1.11 :** *The load connected to a station is 100 kW and the demand factor of the consumers is 1.2. Estimate the capacity of the generating station when load factor is 70 % capacity factor is 60 %. Diversity factor of distribution is 1.3 and that of transmission is 1.5. Take efficiency of transmission and distribution as 90 %.*

Solution : Connected load = 100 kW ; Load factor = 70 %

Demand factor = 1.2 ; Capacity factor = 60 %

Diversity factor for distribution = 1.3

Diversity factor for transmission = 1.5

Efficiency of transmission and distribution = 90 %

$$\text{Load demand factor} = \frac{\text{Connected load}}{\text{Maximum demand}}$$

$$\text{Maximum demand on distribution network} = \frac{100}{1.2} = 83.33 \text{ kW}$$

$$\begin{aligned}\begin{array}{l}\text{Maximum demand on}\\ \text{generating station}\end{array} &= \frac{\text{Maximum demand on distribution network}}{\begin{array}{c}\text{Diversity factor}\\ \text{of distribution}\end{array} \times \begin{array}{c}\text{Diversity factor}\\ \text{of transmission}\end{array} \times \begin{array}{c}\text{Efficiency of transmission}\\ \text{and distribution}\end{array}} \\ &= \frac{83.33}{1.3 \times 1.5 \times 0.9} \\ &= 47.48 \text{ kW}\end{aligned}$$

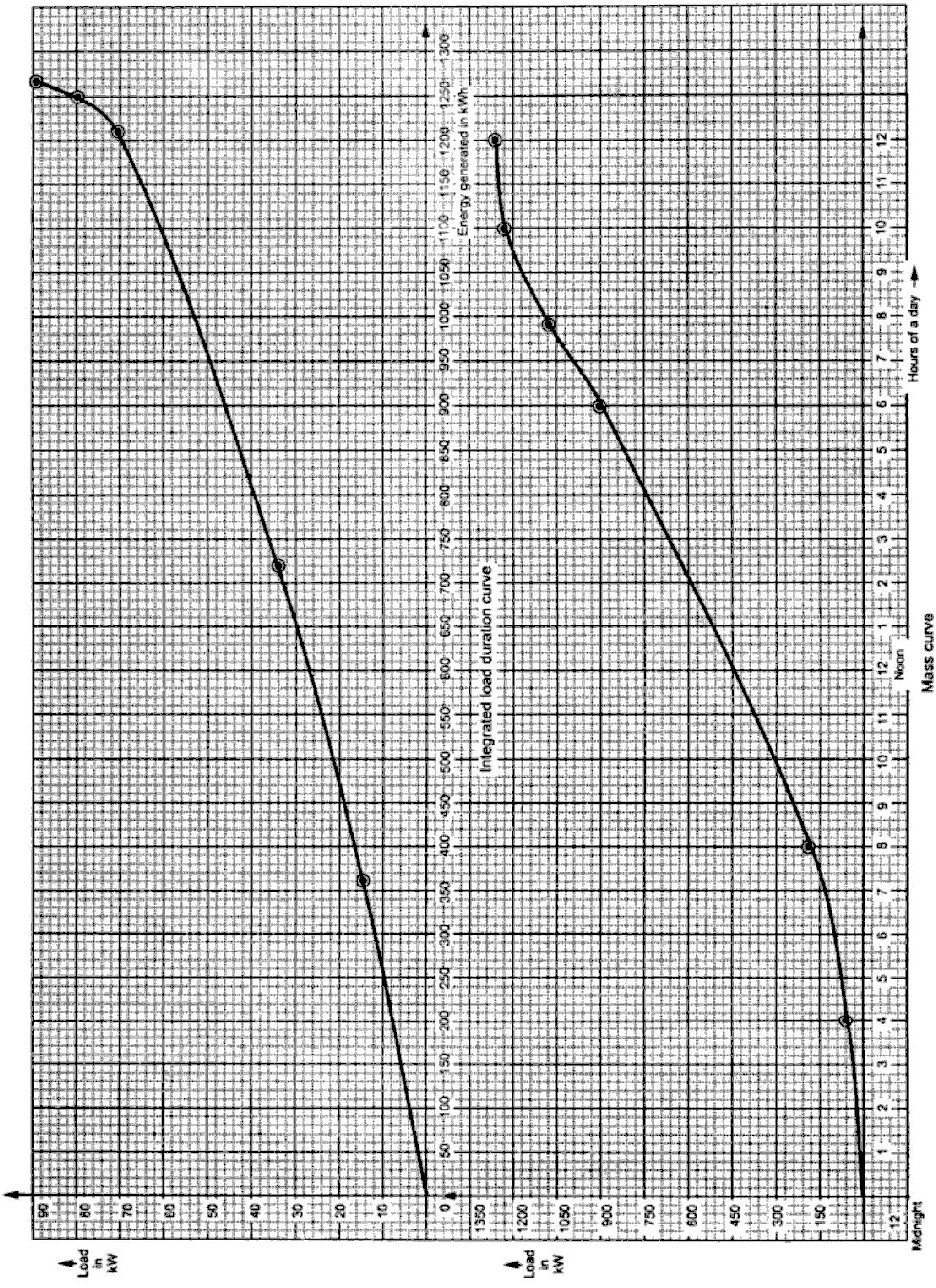

Energy generated in kWh
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050
1100
1150
1200
1250
1300
Integrated load duration curve
Load in kW
90
80
70
60
50
40
30
20
10
Load in kW
1350
1200
1050
900
750
600
450
300
150
Mass curve
Hours of a day
Midnight
12
1
2
3
4
5
6
7
8
9
10
11
12
Noon
1
2
3
4
5
6
7
8
9
10
11
12

Fig. 1.35

Now $\text{Load factor} = \dfrac{\text{Average load}}{\text{Maximum demand}}$ $\therefore$ Average load = Load factor × Maximum demand

$$\text{Capacity factor} = \frac{\text{Average load}}{\text{Plant capacity}} = \frac{\text{Load factor} \times \text{Maximum demand}}{\text{Plant capacity}}$$

$$\therefore \quad \text{Plant capacity} = \frac{\text{Maximum demand} \times \text{Load factor}}{\text{Capacity factor}}$$

$$\therefore \quad \text{Plant capacity} = \frac{47.48 \times 0.7}{0.6} = \mathbf{55.39\ kW}$$

Example 1.12 : *The peak load on a 60 MW power station is 50 MW. It supplies power through four transformers whose connected loads are 20, 14, 10 and 12 MW. The maximum demands on these transformers are 19, 13, 9 and 10 MW respectively. If the annual load factor is 60 % and the plant is operating for 70 % of the period in the year. Find out*

i) Average load on the station ii) Energy supplied per year iii) Demand factor iv) Diversity factor v) Use factor of the power station.

Solution : Power station capacity = 6 MW

Maximum demand = 50 MW

Sum of connected loads = 20 + 14 +10 +12 = 56 MW

Sum of maximum demand on transformers = 19 + 13 + 9 + 10 = 51 MW

Plant load factor = 60 % = 0.6

Plant operating period = 70 % of period in year = 0.7 × 8760

= 6132 Hours

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}}$$

$$\therefore \quad \text{Average load} = \text{Load factor} \times \text{Maximum demand}$$

$$\therefore \quad \text{Average load} = 0.6 \times 50 = \mathbf{30\ MW}$$

Units generated in a year = Average load × Hours of year

= 30 × 8760 = 262800 MWh

$$\text{Demand factor} = \frac{\text{Maximum demand}}{\text{Connected load}} = \frac{50}{56} = 0.8328$$

$$= \mathbf{83.28\ \%}$$

$$\text{Diversity factor} = \frac{\text{Sum of individual maximum demands}}{\text{Maximum demand}}$$

$$= \frac{51}{50} = \mathbf{1.02}$$

$$\text{Plant use factor} = \frac{\text{Units generated per year}}{\text{Plant capacity} \times \text{Hours of operation}}$$

$$= \frac{262800}{60 \times 6132}$$

$$= \mathbf{0.7142 \text{ or } 71.42\ \%}$$

Example 1.13 : *From a load duration curve following data is available. The maximum demand on the system is 30 MW. The load supplied by two units is 20 MW and 12 MW. Unit 1 acts as a base load unit and unit number 2 as a peak load unit. The base load unit is works of 100 % of the time and peak load unit for only 50 % of the time. The energy generated by unit number 1 is 1 ×* 10^8 *units and that by unit number 2 is 1×* 10^7 *units. Determine the load factor, plant capacity factor and plant use factor of each unit and load factor of the total plant*

Solution : Let the maximum demand on the unit acting as base load equal to its rated capacity i.e. 20 MW.

Peak load on standby unit = Maximum demand on system – Maximum demand on base load plant

$$30 - 20 = 10 \text{ MW}$$

$$\text{Capacity of peak load plant unit} = 12 \text{ MW}$$

$$\text{Annual units generated by peak load unit} = 1 \times 10^7 \text{ kWh}$$

$$\text{Hours of operation of peak load unit} = 0.5 \times 8760 = 4380 \text{ hours}$$

$$\text{Annual average load of peak load unit} = \frac{\text{Annual kWh energy produced}}{\text{Days of year} \times \text{Hrs / day}}$$

$$= \frac{1 \times 10^7}{365 \times 24} = 1141.55 \text{ kW}$$

$$\text{Annual load factor (Peak load unit)} = \frac{\text{Annual average load}}{\text{Maximum demand}} = \frac{1141.55}{10000}$$

$$= 0.1141 = 11.41\ \%$$

$$\text{Plant capacity factor (Peak load unit)} = \frac{\text{Average annual load}}{\text{Plant capacity}} = \frac{1141.55}{12000}$$

$$= 0.09512 = 9.51\ \%$$

$$\text{Plant use factor for peak load unit} = \frac{\text{Annual units produced}}{\text{Plant capacity} \times \text{Hours of operation}}$$

$$= \frac{1\times10^{7}}{12\times10^{3}\times4380}$$

$$= \mathbf{0.1902 \quad or \quad 19.02\ \%}$$

Now let us calculate all the above factors for base unit

$$\text{Annual units generated} = 1\times10^{8} \text{ units}$$

$$\text{Annual average load} = \frac{\text{Annual kWh energy produced}}{\text{Days of year}\times\text{Hours per day}} = \frac{1\times10^{8}}{365\times24}$$

$$= 11415.52 \text{ kW}$$

$$= 11.415 \text{ MW}$$

$$\text{Annual load factor for base load plant} = \frac{\text{Annual average load}}{\text{Maximum demand}} = \frac{11.415}{20}$$

$$= 0.5707 = 57.07\ \%$$

$$\text{Annual capacity factor for base load plant} = \frac{\text{Average load}}{\text{Plant capacity}} = \frac{11.415}{20}$$

$$= 0.5707 = 57.07\ \%$$

$$\text{Plant use factor for base load unit} = \frac{\text{Total units generated (kWh)}}{\text{Rated capacity }\times\text{Hours of use}}$$

$$= \frac{1\times10^{8}}{20\times10^{3}\times8760} = 0.5707 = 57.07\ \%$$

$$\text{Load factor of total plant} = \frac{\text{Total units generated by both units (kWh)}}{\text{Rated capacity of plant}\times\text{Hrs / year}}$$

$$= \frac{(1\times10^{8}+1\times10^{7})}{(20+12)\times10^{3}\times8760} = 0.3924$$

$$= \mathbf{39.24\ \%}$$

Example 1.14 : *For a certain industrial organization maximum and minimum power demands are 40 MW and 10 MW respectively. Its load duration curve can be approximated as shown in the Fig. 1.36. The hydro power available at time of minimum regulated flow is just sufficient to take a peak load of 50 MWh per day. Further it is observed that it will be economical to pump water from tail race to the reservoir by utilizing the steam power plant during the off peak periods and thus running the station at 100 % load factor. Determine the maximum capacity of each type of plant. Assume the efficiency of steam conversion to be 60 %.*

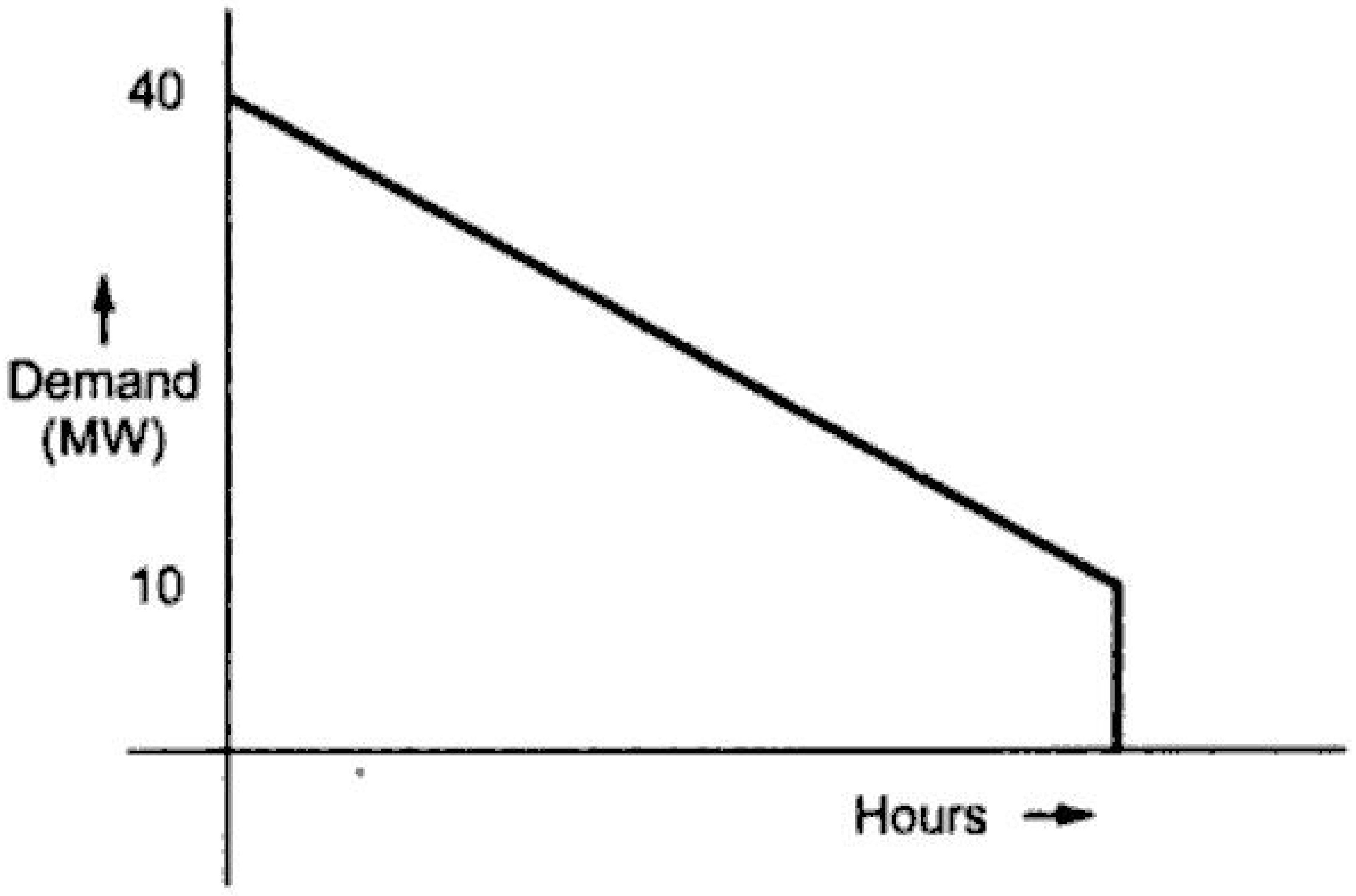


Fig. 1.36

Solution :

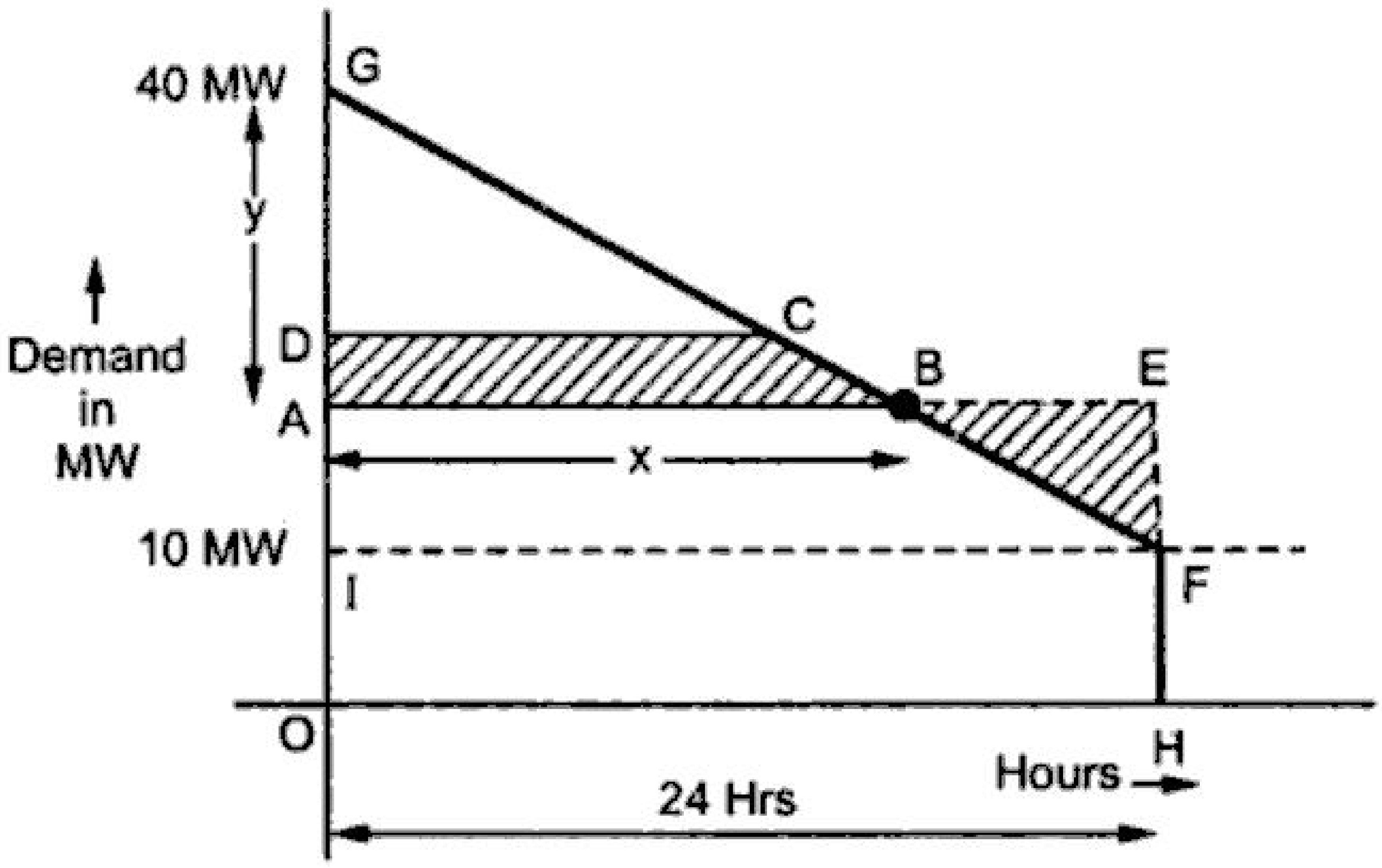


Fig. 1.36 (a)

The total maximum demand is given by OG out of which OA is supplied by steam plant. It can be seen from the load duration curve that the capacity of steam plant given by shaded portion EFB is not utilized efficiently which can be used to pump water in the tail race back to the reservoir. The region GDC of the curve is the hydro energy available during low flow period.

Thus the energy provided by steam plant to the hydro-electric plant is given by area ABCD. As the efficiency of steam plant is 60 %.

$$\text{Area of ABCD} = 0.6 \times \text{Area of EFB} \; \{\because \text{Output by steam plant} = \text{Efficiency} \times \text{Input}$$

$$\text{But area of ABCD} = \text{Area of ABG} - \text{Area GDC}$$

Area GDC is the energy supplied by hydro-electric plant which is 50 MWh.

$$\text{Area of ABCD} = \frac{1}{2}x \cdot y - 50{,}000$$

$$\text{Area of EFB} = \frac{1}{2}(24-x)(30{,}000-y)$$

$$\therefore \quad \frac{1}{2}xy - 50000 = 0.6 \times \frac{1}{2}(24-x)(30{,}000)-y)$$

From similarity of triangles GAB and GIF,

$$\frac{y}{30{,}000} = \frac{x}{24} \qquad \therefore y = \frac{30{,}000x}{24}$$

Substituting in above equation,

$$\frac{1}{2} \times \left[\frac{30{,}000\,x}{24}\right] - 50{,}000 = 0.6 \times \frac{1}{2}(24-x)(30{,}000 - \frac{30{,}000x}{24})$$

$$\frac{30{,}000x^2}{48} - 50{,}000 = 0.3(24-x)\,\frac{720000-30{,}000x}{24}$$

$$\frac{30{,}000x^2-2400000}{48} \qquad \frac{0.3(24-x)(720000-30{,}000x)}{24}$$

$$30{,}000\,x^2 - 2400000 = 0.6\,(24-x)\,(720000-30{,}000x)$$

$$= 0.6\,[17280000-720000x-720000x+30000x^2]$$

$$30000x^2 - 2400000 = 0.6\left[30{,}000x^2 - 1440000x + 17280000\right]$$

$$= 18000\,x^2 - 864000\,x + 13068000$$

$$\therefore \quad 12000x^2 + 864000x - 12768000 = 0$$

$$\therefore \quad 12\,x^2 + 864\,x - 12768 = 0$$

$$\therefore \quad x^2 + 72x - 1064 = 0$$

$$\therefore \quad x = \frac{-72 \pm \sqrt{(72)^2 - 4(1)(-1064)}}{2}$$

$$= \frac{-72 \pm \sqrt{5184+4256}}{2} = \frac{-72 \pm 97.15}{2}$$

$$\therefore \quad x = 12.57 \text{ or } -84.575$$

But x is time in hours which will never be negative.

$$\therefore \quad x = 12.57$$

$$\therefore \quad \text{Capacity of hydroplant} = y = \frac{30{,}000x}{24} = \frac{30{,}000 \times 12.57}{24}$$

$$\therefore \quad y = \mathbf{15.712\ MW}$$

$$\text{Capacity of steam plant} = 40 - 15.712 = \mathbf{24.288\ MW}$$

➠ **Example 1.15 :** *The annual load duration curve for a typical heavy load being served by a steam station, hydro station and a run off river station. The ratio of number of units supplied by these stations are as follows.*

Steam : Run off river : Reservoir hydro :: 8 : 4 : 1

The run off river station is capable of generating power continuously and works as a base load station. The reservoir station works as a peak load station. Determine i) Maximum demand of each station ii) Load factor of each station.

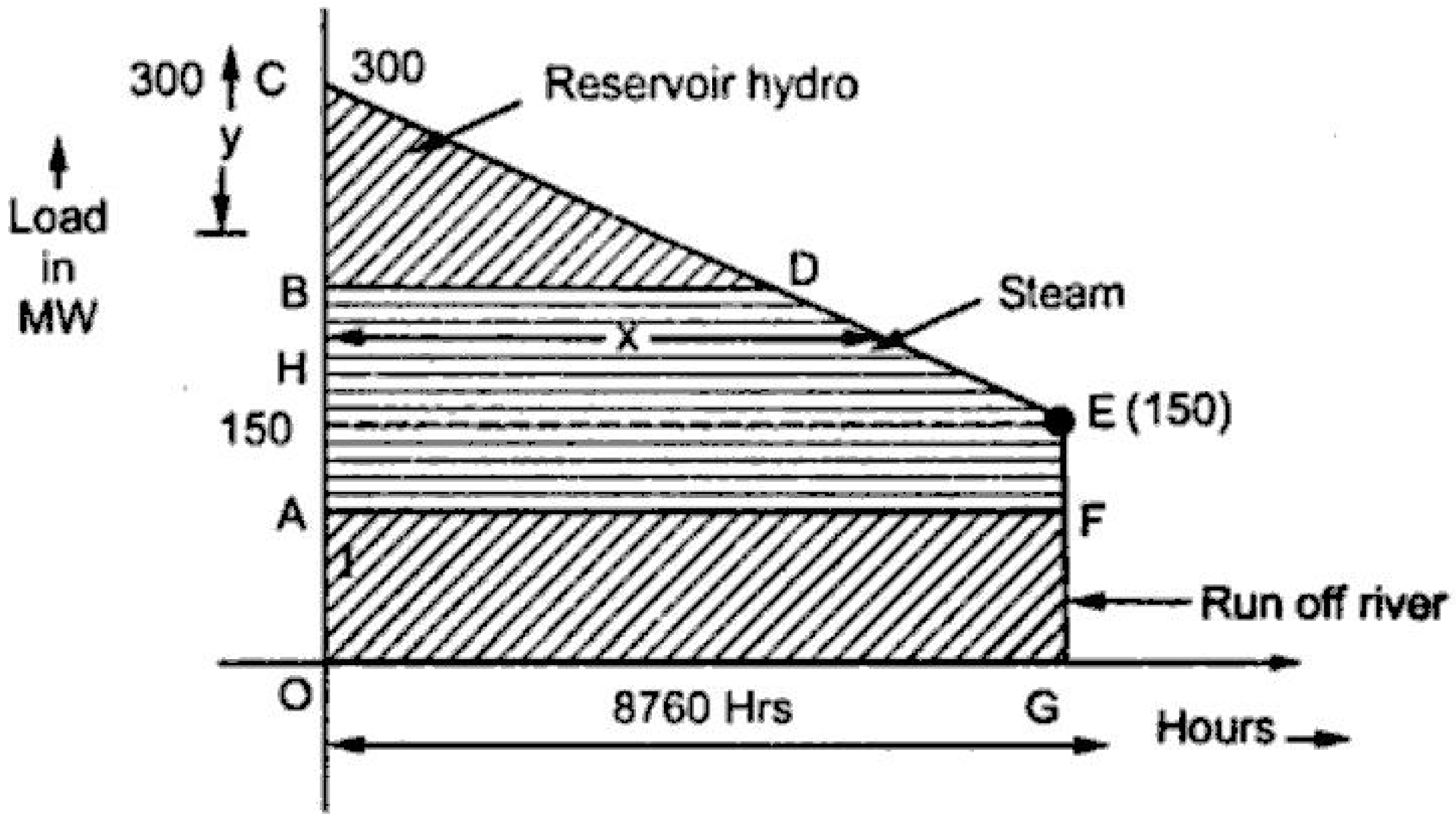


Fig. 1.37

Solution : Let y be the load supplied by reservoir hydro plant and x be its corresponding duration.

$$\text{Units generated / year} = \text{Area in (kWh) under annual load duration}$$

$$= \frac{1}{2}\text{(Sum of parallel sides)} \times \text{Height}$$

$$= \frac{1}{2}(300 + 150) \times 8760 \times 10^3$$

$$= 1971000 \times 10^3 \text{ kWh}$$

$$= 1971 \times 10^6 \text{ kWh}$$

The steam plant, run off river and hydro share the number of units in the ratio 8 : 4 : 1, units generated by each plant are given as,

$$\text{Units generated by steam plant} = \frac{8}{13} \times 1971 \times 10^6 = 1213 \times 10^6 \text{ kWh}$$

$$\text{Units generated by run off river plant} = \frac{4}{13} \times 1971 \times 10^6 = 606 \times 10^6 \text{ kWh}$$

12. Mechanical design aspects which include stress and sag calculations, composition of conductor, spacing of conductor, and configurations for insulators.
13. Design of power system structure.
14. Economical aspects.

2.4 Conductor Types

When the conductors are used in transmission system for bulk power transfer, then they should fulfil following requirements.

1. They should have low weight.
2. They should have high tensile strength.
3. They should have low co-efficient of expansion, low corona loss.
4. They should have less resistance and low cost.

The normally used materials for conductors are copper and aluminium. The advantges of using aluminium conductors over copper conductors are given below.

1. They have low cost
2. Less resistance and corona loss.
3. Less weight.

But aluminium has less tensile strength, high coefficient of expansion and large area which restricts its use alone as a conductor.

In order to increase the tensile strength of a conductor, one or more central conductors of different materials are used. These materials give high tensile strength. The different types of aluminium conductors used in power systems with full forms of their abbrivations are as given below.

AAC : All aluminium conductor.

AAAC : All aluminium alloy conductor.

ACSR : Aluminium conductor with steel reinforcement.

ACAR : Aluminium conductor with alloy reinforcement.

The ACSR conductors are more commonly used as they have following advantages,

1. They have low corona loss.
2. Skin effect is to reduced extent.
3. Due to high mechanical strength, the line span can be increased. This minimizes cost of erection and maintenance.

The voltage drop due to flux linkage is

$$V = j\,\omega LI \quad \text{volts}$$

$$\therefore \quad V = j\,\omega\psi \quad \text{volts}$$

The mutual inductance between the two circuits is defined as the flux linkages of one circuit due to current in the second circuit per ampere of current in the second circuit.

If current I_2 produces ψ_{12} flux linkages with circuit 1, the mutual inductance is

$$M_{12} = \frac{\psi_{12}}{I_2}$$

The voltage drop in circuit 1 is given by

$$V_1 = j\,\omega M_{12} I_2 = j\,\omega\psi_{12} \quad \text{volts}$$

Mutual inductance is important in considering the influence of power lines on telephone lines and the coupling between parallel power lines.

2.7 Capacitance

When any two conductors are separated by an insulating material it will form a capacitor. In case of overhead transmission line air acts as an insulating medium between two conductors. So there will be capacitance between two conductors which is defined as charge per unit potential difference.

$$\text{Capacitance,} \qquad C = \frac{q}{V} \quad \text{Farad}$$

Unlike resistance and inductance, the capacitance of transmission line is also uniformly distributed along the whole length of the line. It may be treated as a uniform series of capacitors connected between the conductors as shown in the Fig. 2.7 and Fig. 2.8.

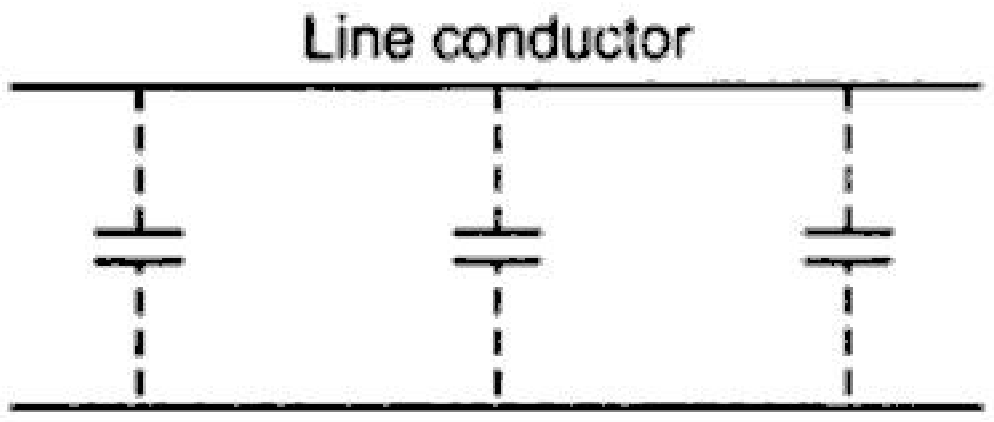


Fig. 2.7

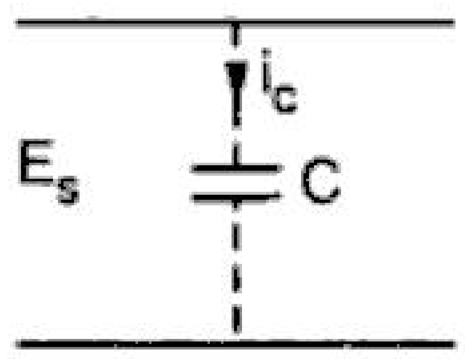


Fig. 2.8

The charge on the conductors at any point increases and decreases with increase and decrease of the instantaneous value of the voltage between conductors at that point. Due to this a current known as charging current flows through the conductors even though the line is open circuited. The voltage drop, efficiency and power factor of line depends on the value of capacitance.

$$= \frac{\mu I}{2\pi}\int_{D_1}^{D_2}\frac{dx}{x} = \frac{\mu I}{2\pi}\,ln\left(\frac{D_2}{D_1}\right)$$

$$\because \qquad \mu = \mu_0\,\mu_r$$

For relative permeability, $\mu_r = 1$

$$\psi_{12} = \frac{\mu_0 I}{2\pi}\,ln\left(\frac{D_2}{D_1}\right)$$

$$= \frac{4\pi\times10^{-7}\,I}{2\pi}\,ln\left(\frac{D_2}{D_1}\right)$$

$$\psi_{12} = 2\times10^{-7}\,I\,ln\left(\frac{D_2}{D_1}\right)$$

The inductance due to flux included between P_1 and P_2 only is,

$$L_{12} = \frac{\psi_{12}}{I} = 2\times10^{-7}\,ln\left(\frac{D_2}{D_1}\right)$$

In the external flux is considered to be extended from the surface of conductor to infinity then total flux linkages is given by,

$$\psi_{12} = \int_{r}^{\infty}\frac{\mu_0 I}{2\pi x}\,dx \quad \text{weber-turns}$$

Overall flux linkages is given by

$$\text{Total flux linkage} = \frac{\mu_0 I}{8\pi} + \int_{r}^{\infty}\frac{\mu_0 I}{2\pi x}\,dx = \frac{\mu_0 I}{2\pi}\left[\frac{1}{4}+\int_{r}^{\infty}\frac{dx}{x}\right]$$

2.10 Inductance of a Single Phase Two Wire Line

Consider a single phase line consisting of two parallel conductors. These conductors are forming a rectangular loop of one turn. These conductors are solid conductors of radii r_1 and r_2 respectively. One conductor is forming a return circuit for the other. The two conductors are carrying currents I_1 and I_2 respectively.

In a single phase circuit we have

$$I_1 + I_2 = 0$$

$$\therefore \qquad I_2 = -I_1$$

Here we are neglecting the effect of earth's presence of magnetic field geometry as earth's relative permeability is same as that of air and its conductivity is relatively small.

Now ψ_{1p2} is the flux linkage of conductor 1 due to current I_2 is equal to flux produced by I_2 between the point P and conductor 1. Again flux beyond P is neglected.

$$\psi_{1p2} = 2 \times 10^{-7}\, I_2\, ln \frac{D_{2p}}{D_{12}}$$

Similarly the flux linkages ψ_{1p} with conductor 1 due to all the conductors in the group but the flux beyond point P is neglected.

$$\psi_{1p} = 2 \times 10^{-7} \left[I_1\, ln \frac{D_{1p}}{r_1'} + I_2\, ln \frac{D_{2p}}{D_{12}} + I_3\, ln \frac{D_{3p}}{D_{13}} + \ldots + I_n\, ln \frac{D_{np}}{D_{1n}} \right]$$

By expanding the logarithmic terms and rearranging the terms

$$\psi_{1p} = 2 \times 10^{-7} \left[\begin{array}{l} I_1\, ln \frac{1}{r_1'} + I_2 ln \frac{1}{D_{12}} + I_3 ln \frac{1}{D_{13}} + \ldots + I_n\, ln \frac{1}{D_{1n}} \\ + I_1 ln D_{1p} + I_2 ln D_{2p} + I_3\, ln D_{3p} + \ldots + I_n\, ln D_{np} \end{array} \right]$$

The sum of all currents is zero.

$I_1 + I_2 + I_3 + \ldots + I_n = 0$

$$I_n = -(I_1 + I_2 + \ldots + I_{n-1})$$

Substituting this value in above equation

$$\psi_{1p} = 2 \times 10^{-7} \left[\begin{array}{l} I_1\, ln \frac{1}{r_1'} + I_2 ln \frac{1}{D_{12}} + \ldots + I_n\, ln \frac{1}{D_{1n}} + I_1 ln D_{1p} \\ + I_2 ln\, D_{2p} + \ldots (-I_1 - I_2 \ldots - I_{n-1}) ln\, D_{np} \end{array} \right]$$

$$\psi_{1p} = 2 \times 10^{-7} \left[\begin{array}{l} I_1\, ln \frac{1}{r_1'} + I_2\, ln \frac{1}{D_{12}} + \ldots + I_n\, ln \frac{1}{D_{1n}} + I_1 ln \left(\frac{D_{1p}}{D_{np}} \right) \\ + I_2\, ln \left(\frac{D_{2p}}{D_{np}} \right) + \ldots + I_{n-1}\, ln \left[\frac{D_{(n-1)P}}{D_{np}} \right] \end{array} \right]$$

If point P is at infinite distance so that $ln \frac{D_{1p}}{D_{np}}\; ln \frac{D_{2p}}{D_{np}}$ etc will approach to zero (since $ln\, 1 = 0$) then we have,

$$\psi_{1p} = 2 \times 10^{-7} \left[I_1\, ln \frac{1}{r_1'} + I_2\, ln \frac{1}{D_{12}} + \ldots + I_n ln \frac{1}{D_{1n}} \right]$$

If $\quad r_1' = D_{11}$ then

$$\psi_{1p} = 2 \times 10^{-7} \left[I_1\, ln \frac{1}{D_{11}} + I_2 ln \frac{1}{D_{12}} + \ldots + I_n ln \frac{1}{D_{1n}} \right]$$

table. To that value, the value of inductive reactance spacing factor is added which is also available at desired line frequency.

2.14 Flux Linkages in Parallel Current Carrying Conductors

Consider a group of parallel conductors A, B, C etc as shown in the Fig. 2.15. Each of these conductors carry current I_A, I_B, I_C etc.

Consider the flux linkages with any one conductor say A. There will be flux linkages with conductor A due to its own current. Also there will be flux linkages with this conductor due to mutual inductance effects.

Flux linkages with conductor A due to its own current,

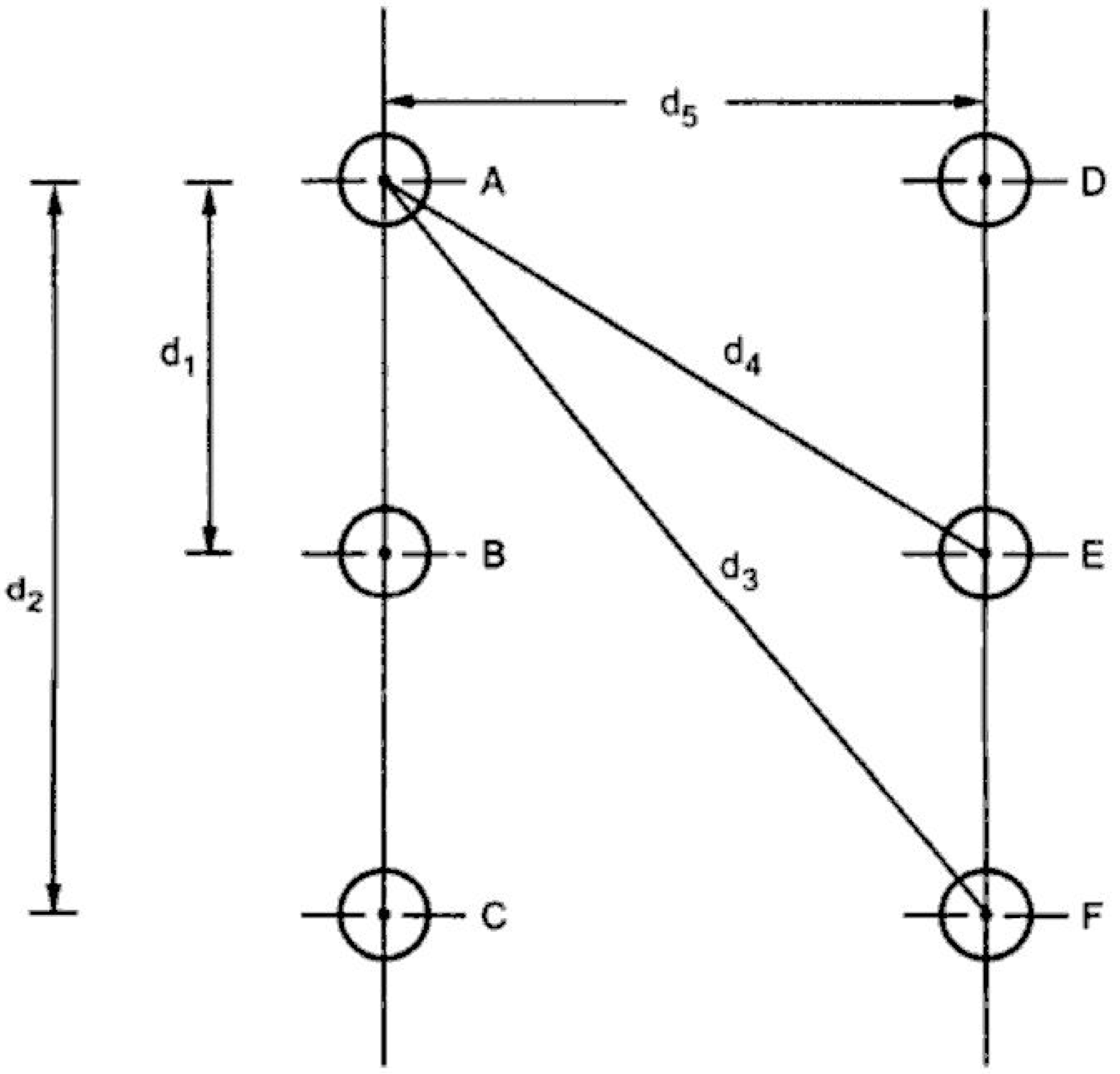


Fig. 2.15

$$\psi_{1A} = \frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4}+\int_r^{\infty}\frac{dx}{x}\right]$$

Flux linkages with conductor A due to the current I_B,

$$\psi_{1B} = \frac{\mu_0 I_B}{2\pi}\left[\int_{d_1}^{\infty}\frac{dx}{x}\right]$$

2.17 Inductance of Three Phase Line with Unsymmetrical Spacing but Transposed

Now consider a three phase line having three conductors but not spaced equilaterally. The problem of finding the inductance in this case is difficult. The flux linkage and the corresponding inductance will not be same in each phase. Due to this different inductance per phase there is unbalance in the circuit though the currents in each phases are balanced.

The drops in the three phases due to these inductances are observed to be different. Thus at the receiving end we will not get the same voltage.

In order to achieve balance under this case, transposition of transmission line is preferred after a certain fixed distance. This is shown in the Fig. 2.18.

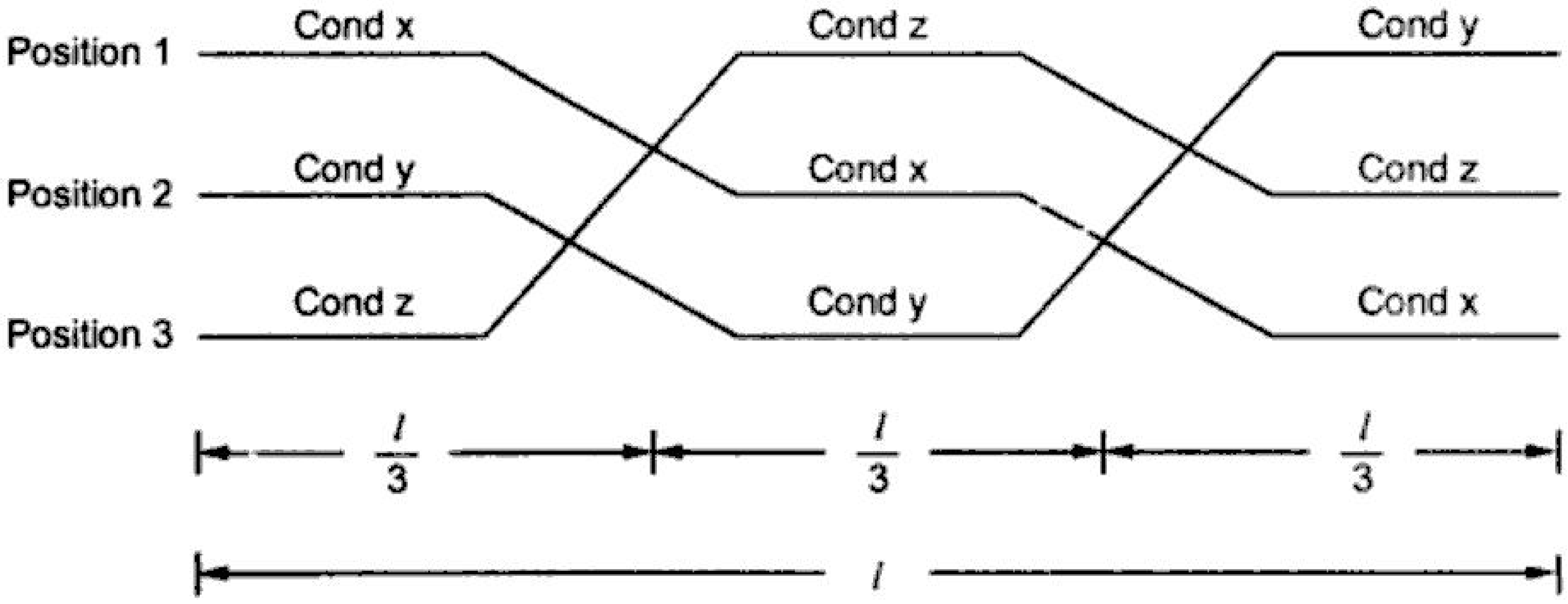


Fig. 2.18

The positions of the conductors are exchanged at regular interval along the line so that each conductor occupies the original position of every other conductor over an equal distance. This exchange of conductor positions is called transposition. Thus balance in the three phase is restored.

The Fig. 2.18 shows complete transposition cycle. The conductors in the individual phases are denoted by x, y and z where the positions are given by 1, 2, and 3. The same average inductance over the complete cycle is obtained due to the transposition.

The average inductance of one conductor is obtained by finding the flux linkages of a conductor for each position that is occupied during a complete cycle of transposition. Then the average flux linkages are obtained.

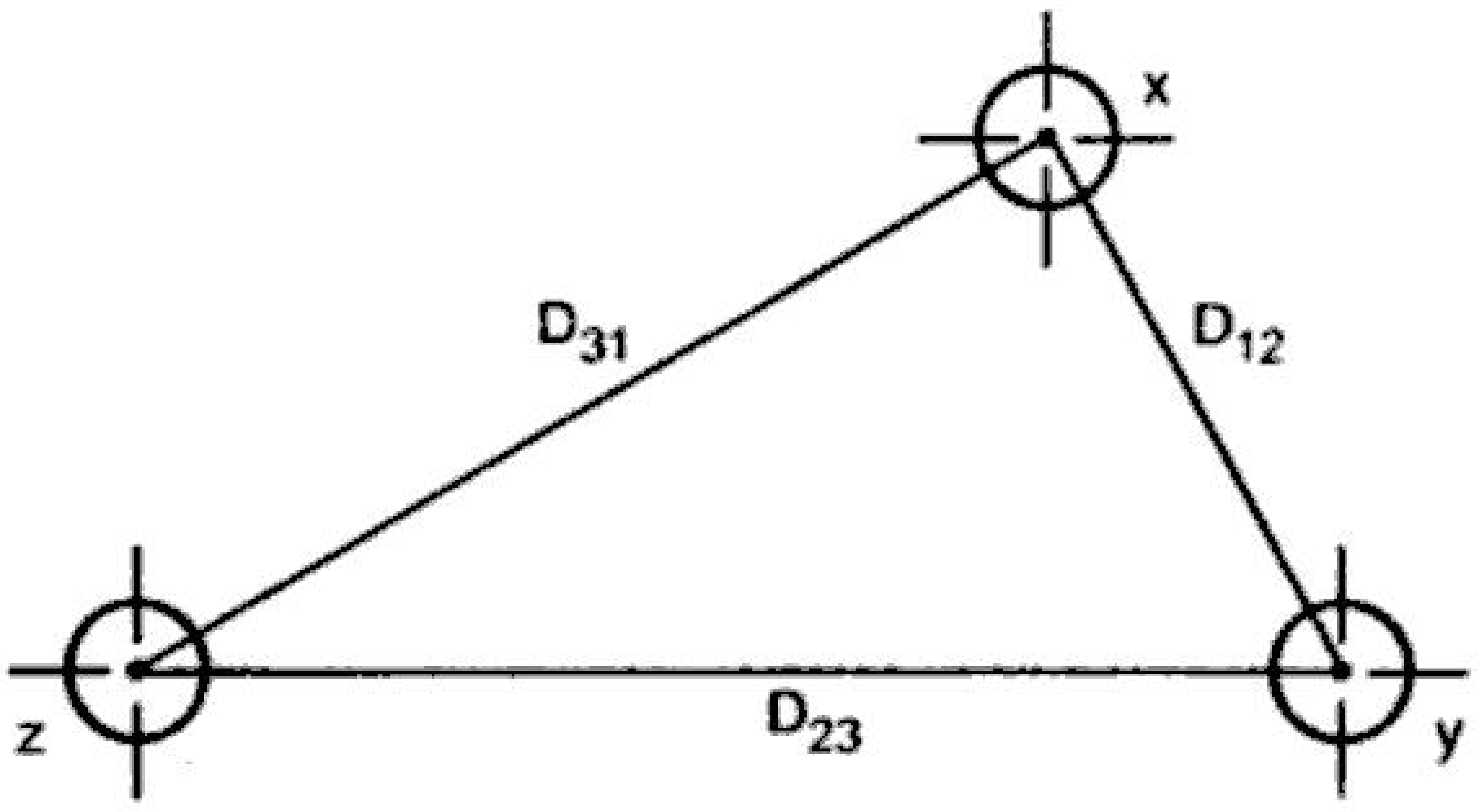


Fig. 2.19

$$L_x = \frac{\psi_x}{I_x} = 2 \times 10^{-7} \; ln\left(\frac{\sqrt{3}D}{2r'}\right) H/m$$

As the conductors are in parallel,

Inductance of each conductor = $2L_x$

$$= 4 \times 10^{-7} \; ln\left(\frac{\sqrt{3}D}{2r'}\right) H/m$$

2.20 Inductance of Three Phase Double Circuit with Unsymmetrical Spacing but Transposed

Consider three phase double circuit having conductors which are unsymmetrically spaced. The line is transposed so that each conductor occupies the position of other conductor after certain interval length or distance of transmission line.

The transposition cycle is as shown in the Fig. 2.23.

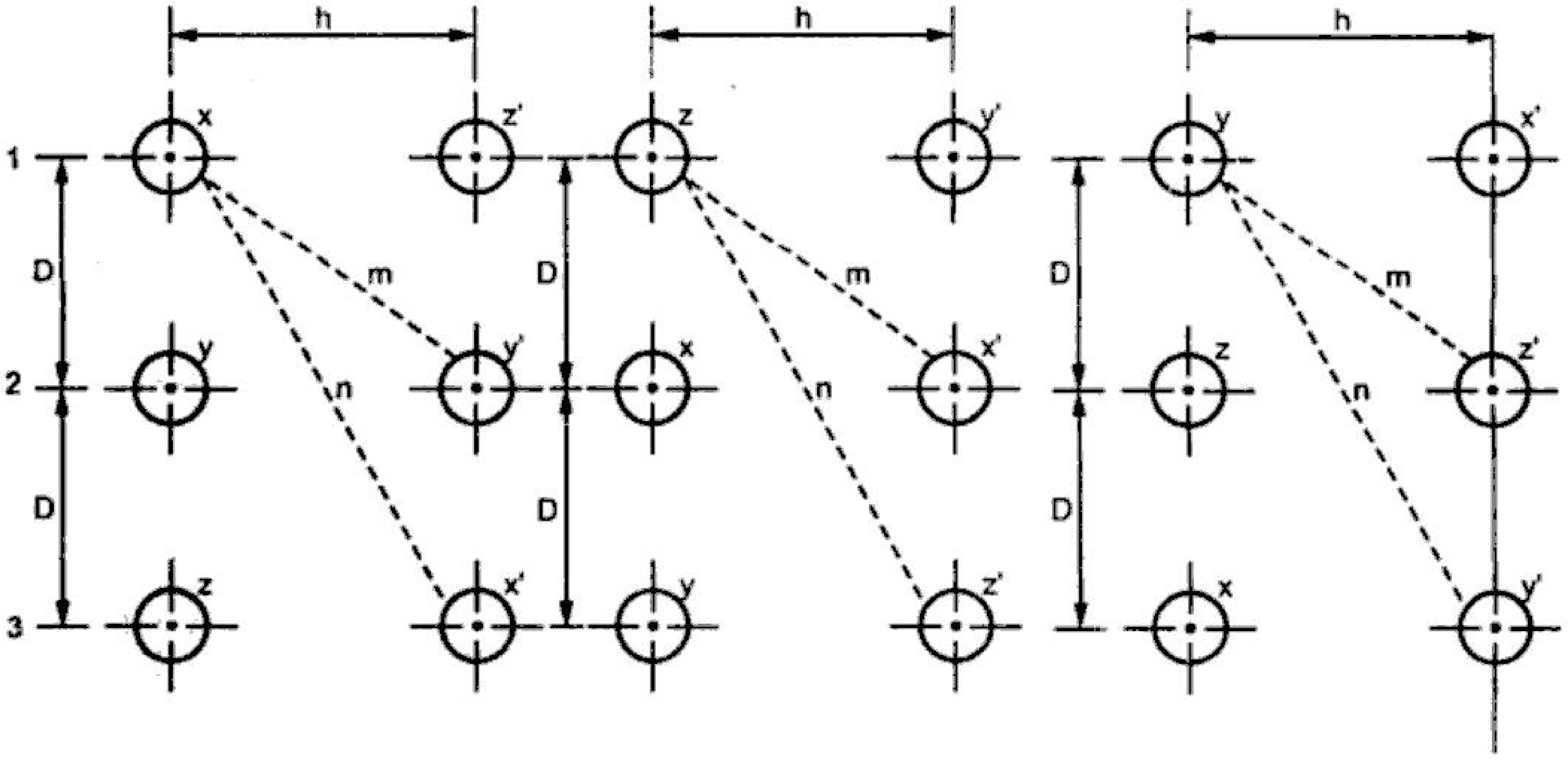


Fig. 2.23

Flux linkage of conductor x in position 1

$$\psi_{x1} = 2 \times 10^{-7} \left\{ I_x\left(ln\frac{1}{r'} + ln\frac{1}{n} \right) + I_y\left(ln\frac{1}{D} + ln\frac{1}{m} \right) + I_z\left(ln\frac{1}{2D} + ln\frac{1}{h} \right) \right\}$$

Similarly,

$$\psi_{x2} = 2 \times 10^{-7} \left\{ I_x\left(ln\frac{1}{r'} + ln\frac{1}{h} \right) + I_y\left(ln\frac{1}{D} + ln\frac{1}{m} \right) + I_z\left(ln\frac{1}{D} + ln\frac{1}{m} \right) \right\}$$

$$= 4 \times 10^{-4}\, ln\left(\frac{D_m}{D_s}\right) H/km$$

$$D_m = \sqrt[4]{D_{ab} D_{ab'} , D_{ba'} , D_{ba}}$$

$$= \sqrt[4]{(0.3)\,(1.0440)\,(1.0440)\,(0.3)}$$

$$= 0.5596 \text{ m}$$

$$D_s = \sqrt[4]{D_{aa}\, D_{aa'} , D_{a'a}\, D_{a'a'}}$$

$$= \sqrt[4]{(3.894 \times 10^{-3})\,(1)\,(1)\,(3.894 \times 10^{-3})}$$

$$= 0.06240 \text{ m}$$

$$\text{Loop inductance} = 4 \times 10^{-4}\, ln\left(\frac{0.5596}{0.06240}\right)$$

$$= 3.5871 \times 10^{-3} \text{ H/km}$$

Loop inductance/km = **3.5871 mH**

Example 2.4 : *A single phase overhead line 25 km long is to be constructed of conductor 1.5 cm diameter. Calculate the maximum spacing between the conductors in order that the loop inductance of conductor is not more than 0.08 H.*

Solution : Length of transmission Line = 25 km = 25000 m

$$\text{Loop inductance per metre of transmission Line} = \frac{0.08}{25000} = 3.2 \times 10^{-6} \text{ H}$$

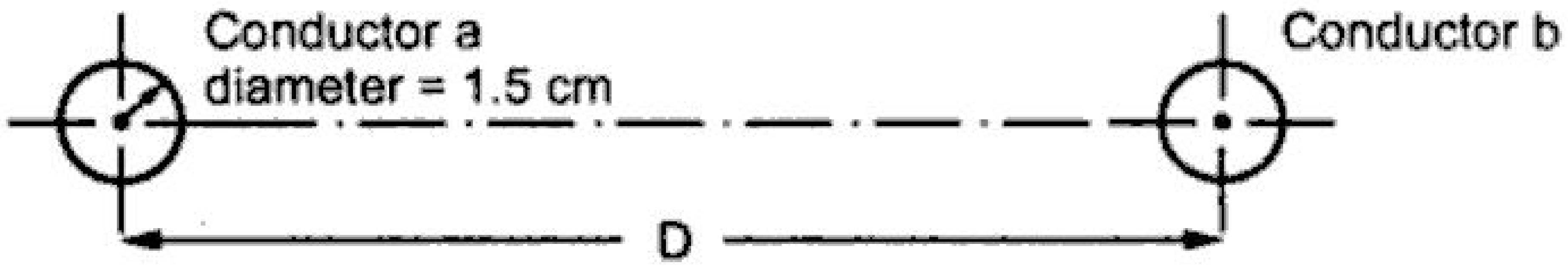


Fig. 2.27

$$\text{Diameter of conductor} = 1.5 \text{ cm}$$

$$\text{Radius of conductor} = 0.75 \text{ cm}$$

$$r' = 0.7788 \times \text{Radius of conductor}$$

$$= 0.7788 \times 0.75 = 0.5841 \text{ cm}$$

$$= 5.841 \times 10^{-3} \text{ m}$$

$$\text{Loop inductance per metre of the line} = 4 \times 10^{-7}\left(\frac{D}{r'}\right)$$

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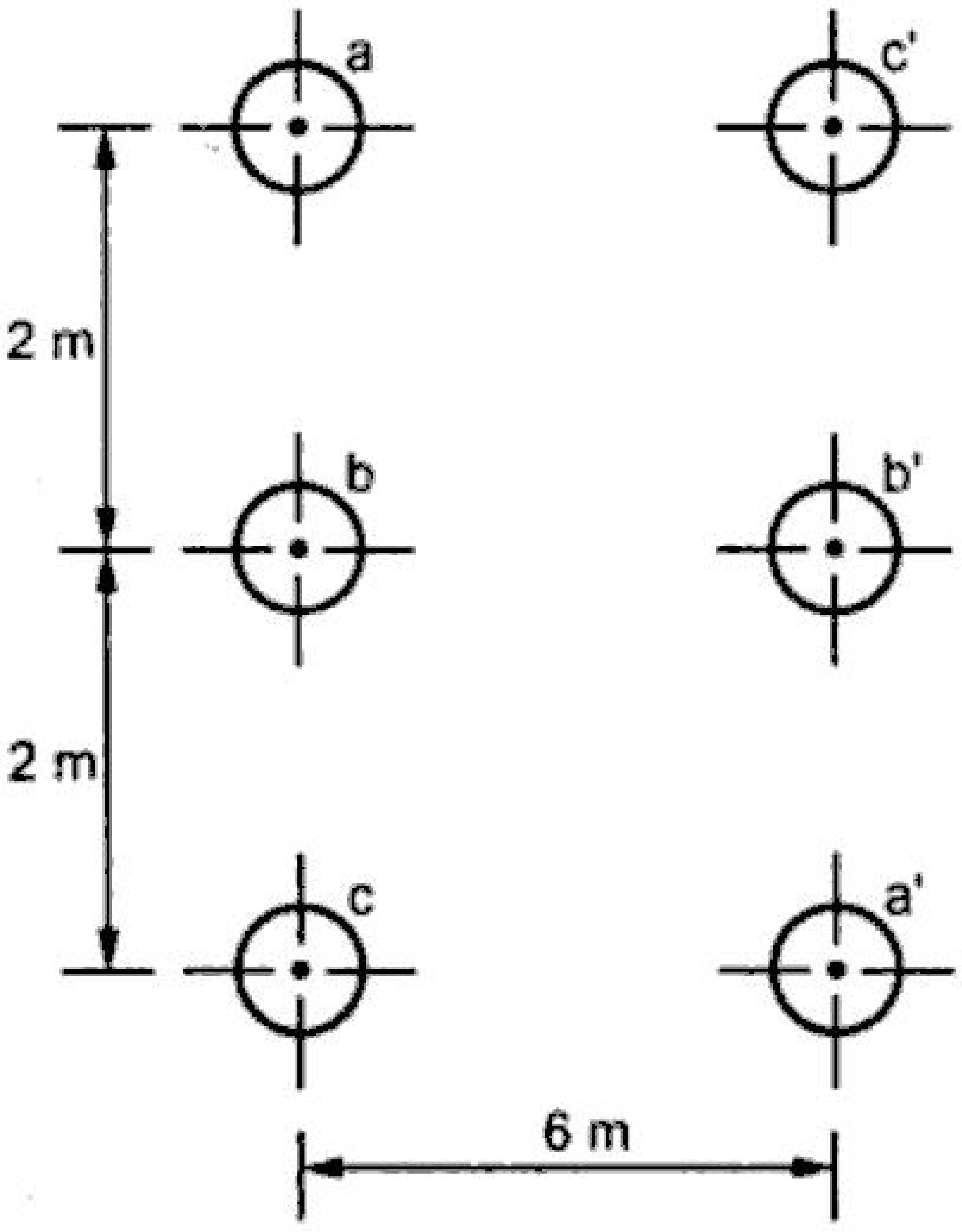


Fig. 2.31

Solution : $r' = 0.7788 \times 1.5 = 1.1682 \text{ cm} = 0.011682 \text{ m}$

$$D_{ab'} = \sqrt{6^2+2^2} = 6.3245 \text{ m} = D_{ba'}$$

$$D_{aa'} = \sqrt{6^2+4^2} = 7.2111 \text{ m}$$

$$D_S = \sqrt[3]{D_{s1}D_{s2}D_{s3}}$$ D_{s1}, D_{s2}, D_{s3} represent self G.M.D. in position 1, 2 and 3 respectively

$$D_{S1} = \sqrt[4]{D_{aa}\ D_{aa'}\ D_{a'a}\ D_{a'a'}}$$
$$= \sqrt[4]{(0.011682)\ (7.2111)\ (7.2111)\ (0.011682)}$$
$$= 0.2902 \text{ m} = D_{s3}$$

$$D_{S2} = \sqrt[4]{D_{bb}\ D_{bb'}\ D_{b'b}\ D_{b'b'}} = \sqrt[4]{(0.011682)\ (6)\ (6)\ (0.011682)}$$
$$= 0.2647 \text{ m}$$

$$D_S = \sqrt[3]{D_{s1}D_{s2}D_{s3}} = \sqrt[3]{(0.2902)\ (0.2647)\ (0.2902)} = 0.1493 \text{ m}$$

Equivalent mutual GMD,

$$D_m = \sqrt[3]{D_{AB}D_{BC}D_{CA}}$$

$$D_{AB} = \sqrt[4]{D_{ab}D_{ab'}D_{ba}\,D_{ba'}} = \sqrt[4]{(2)\ (6.3245)\ (2)\ (6.3245)}$$
$$= 3.5565 \text{ m}$$

$$D_{BC} = \sqrt[3]{D_{bc}D_{bc'}D_{cb}D_{cb'}} = \sqrt[4]{(2)\ (6.3245)\ (2)\ (6.3245)}$$

voltage between the conductors. Due to alternate charging and discharging of line, current starts flowing in the line. This current is known as charging current. This current flows even when the line is open circuited. The voltage drop along the line is affected. It also affects the efficiency and power factor of the line. Stability of the system is also affected because of this.

2.22 Electric Field of a Long Straight Conductor

Before we proceed for the concept of Electric field let us first see what do you mean by electrical potential. Electrical potential at a point due to a charge is the amount of work done in bringing a unit positive charge from infinity to that point. The concept of electrical potential is important for the evaluation of the capacitance.

While considering the inductance, magnetic field is important. Similarly while working with capacitance, electric field plays important role. Lines of electric flux originate on the positive charges of one conductor and terminate on the negative charges of other conductor. The total electric flux emanating from a conductor is numerically equal to the number of coulambs of charge on the conductor. Electric flux density is the electric flux per square metre and is measured in coulambs per square metre.

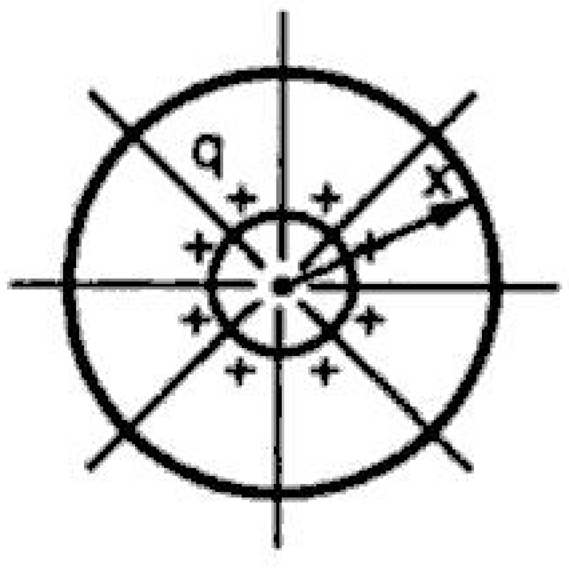


Fig. 2.34

Consider a long, straight cylindrical conductor placed in uniform medium such as air as shown in the Fig. 2.34. It has uniform charge along its entire length. It is isolated from other charges so that the charge is uniformly distributed around the periphery. The flux lines are radial.

The electric flux density at x meters from the conductor can be obtained by assuming a cylindrical surface concentric with the conductor and x metres in radius. As all the parts of the surface are at the same distance from the conductor having uniformly distributed charge, the cylindrical surface is a surface of equipotential and the electric flux density on the surface is equal to the flux leaving the conductor per metre of length divided by the area of the surface in an axial length of 1 m.

Electric flux density, $$D = \frac{q}{2\pi x} \quad c/m^2$$

Here q is the charge on the conductor and x is the distance from the conductor to the point where it is required to find field intensity. If the field desnsity is divided by the permittivity of the medium then we get the field intensity.

Electric field intensity, $$E = \frac{D}{\varepsilon} = \frac{q}{2\pi\varepsilon x}$$

Permittivity, $\varepsilon = \varepsilon_0 \varepsilon_r$ where

ε_0 = Permittivity of free space = 8.85×10^{-12} F/m

ε_r = Relative permittivity

As x approaches infinity, the value of E approaches zero. Therefore the potential difference between conductor and neutral plane at infinity distance where E and potential is zero, is given by,

$$V_A = \int_r^\infty \frac{Q_A}{2\pi\varepsilon_0 x} dx = \frac{Q_A}{2\pi\varepsilon_0} \int_r^\infty \frac{d_x}{x}$$

2.23 Potential Difference between Two Points due to a Charge

The potential difference between any two points is nothing but the work done in joules per coulomb required to move a coulomb of charge between the two points. The force on a charge in the field is measured by electric field intensity which is equal to the force in newtons per coulomb on a coulomb of charge at the point considered and is measured in volts per metre.

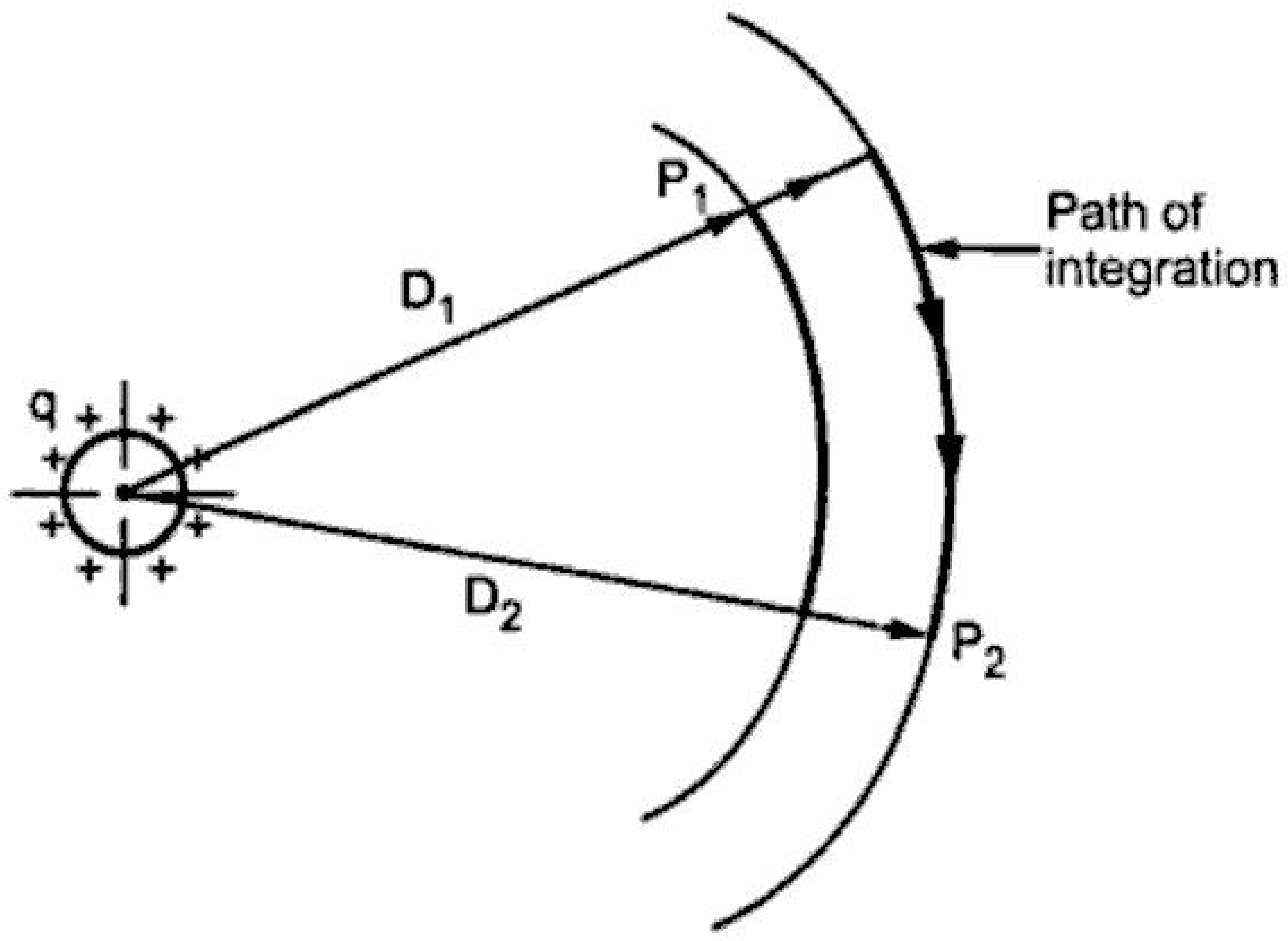


Fig. 2.35

Consider a long straight wire carrying positive charge of q c/m as shown in the Fig. 2.35.

Consider two points P_1 and P_2 located at a distances of D_1 and D_2 from centre of wire. There is positive charge on wire which will repel when a positive charge is placed in the field. If we want to move charge from point P_2 to P_1 then work must be done on positive charge. Here P_1 is at higher potential than P_2. If the charge moves from P_1 to P_2, it expends energy which is nothing but voltage drop from P_1 to P_2. The path followed does not affect the potential difference.

In order to find the voltage drop from P_1 to P_2 is to obtain the voltage between equipotential surfaces passing through P_1 and P_2.

The voltage drop between P_1 and P_2 is,

$$V_{12} = \int_{D_1}^{D_2} E \cdot dx = \int_{D_1}^{D_2} \frac{q}{2\pi\varepsilon x} dx = \frac{q}{2\pi\varepsilon} \int_{D_1}^{D_2} \frac{d_x}{x}$$

$$= \frac{q}{2\pi\varepsilon} \ln\left[\frac{D_2}{D_1}\right]$$

The voltage drop between two points may be either positive or negative depending upon the charge causing the potential difference is positive or negative. It also depends upon whether the voltage drop is computed from a point near the conductor to a point far away or viceversa.

2.24 Capacitance of Single Phase Line

Capacitance between the two conductors of a two wire line is the charge on he conductors per unit of potential difference between them. Capacitance of the line per unit length is given by

$$C = \frac{q}{v}\ \text{F/m}$$

The capacitance of single phase line is obtained by substituting in above equation v in terms of q.

Consider a single phase overhead transmission line consisting of two conductors 'a' and 'b' which are separated by a distance of D in air as shown in the Fig. 2.36. The charges on each conductors are respectively +q and −q coulombs per metre length.

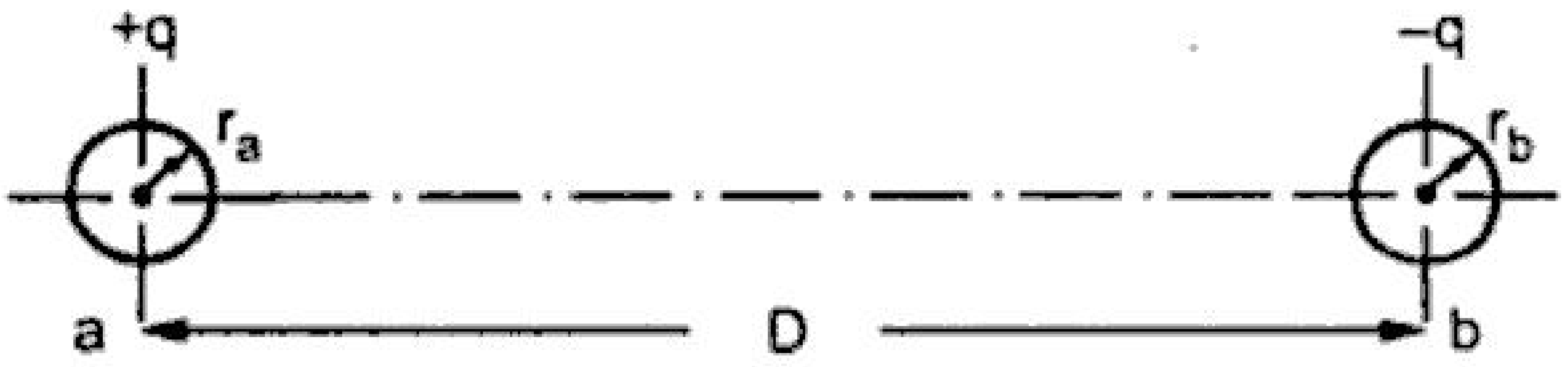


Fig. 2.36

The voltage V_{ab} between the two conductors can be obtained by finding the potential difference between the two conductors of the line. Firstly let us find the voltage drop due to charge q on conductor a and then finding voltage drop due to charge −q on conductor b. Then by using principle of superposition the voltage drop between conductor a and b is obtained by adding the voltage drops caused by each charge alone.

The voltage drop V_{ab} is therefore given by

$$V_{ab} = (V_{ab} \text{ due to } + q) + (V_{ab} \text{ due to } - q)$$

$$V_{ab} = \left(\frac{q}{2\pi\varepsilon}\right) ln\frac{D}{r_a} + \left(\frac{-q}{2\pi\varepsilon}\right) ln\left(\frac{r_b}{D}\right)$$

$$= \left(\frac{q}{2\pi\varepsilon}\right)\left[ln\frac{D}{r_a} - ln\frac{r_b}{D}\right]$$

$$V_{ab} = \left(\frac{q}{2\pi\varepsilon}\right) ln\left(\frac{D^2}{r_a\, r_b}\right) \text{volts}$$

The capacitance between the conductors is given by

$$C_{ab} = \frac{q}{V_{ab}} = \frac{2\pi\varepsilon}{ln\left(\frac{D^2}{r_a r_b}\right)} \text{ F/m} = \frac{2\pi\varepsilon_0\varepsilon_r}{ln\left(\frac{D^2}{r_a r_b}\right)} \text{ F/m}$$

For air $\varepsilon_r = 1$

$$\therefore \quad C_{ab} = \frac{2\pi\varepsilon_0}{ln\left(\frac{D^2}{r_a r_b}\right)}$$

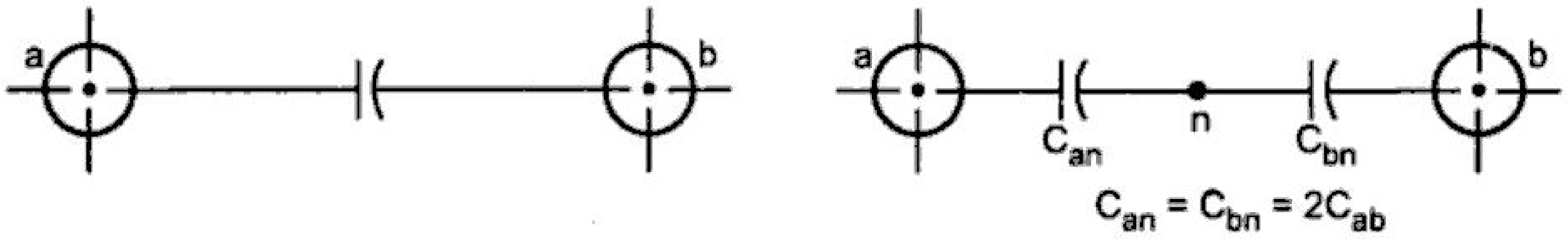
If we take $r_a = r_b = r$ then

$$C_{ab} = \frac{2\pi\varepsilon_0}{ln\left(D^2/r^2\right)} = \frac{\pi\varepsilon_0}{ln(D/r)} \text{ F/m}$$

If it is required to find the capacitance between one of the conductors and the neutral point then it is given by,

$$C_n = C_{an} = C_{bn} = \frac{2\pi\varepsilon_0}{ln(D/r)}$$

The idea of capacitance to neutral is shown in the Fig. 2.37.



(a) Representation of line to line capacitance

(b) Representation of line to neutral capacitance

Fig. 2.37

The equations derived so far related to the capacitance are based on the assumption of uniform charge distribution over the surface of the conductor. In presence of other charges, the distribution will not be uniform and the equations which are derived will not give accurate results. However the nonuniformity of charge distribution can be neglected in case of overhead lines as only 0.010 % of error is caused for a close spacing of ratio of D/r = 50.

If instead of a solid round conductor, we have a stranded conductor then the above equation will produce error slightly. The error will be small as only the field very close to the surface of the conductor is affected. The electric flux at the surface of stranded conductor is not the same as the field at the surface of cylindrical conductor. The outside radius of conductor is used for evaluating capacitance.

If we are having the value of C_{an} then capacitive reactance can be easily obtained.

Permittivity of free air taken as unity.

Capacitive reactance, $X_C = \frac{1}{2\pi f C} = \frac{2.862}{f} \times 10^9 \, ln \frac{D}{r} \, \Omega\text{-m}$

The above expression gives X_C for 1 m of line since capacitive reactance is in parallel along the line, X_C is divided by the length of line in meters to obtain the value of X_C in ohms to neutral for entire length of line. Standard tables are available for outside diametes of most widely used sizes of ACSR.

2.25 Capacitance of a Three Phase Line with Equilateral Spacing

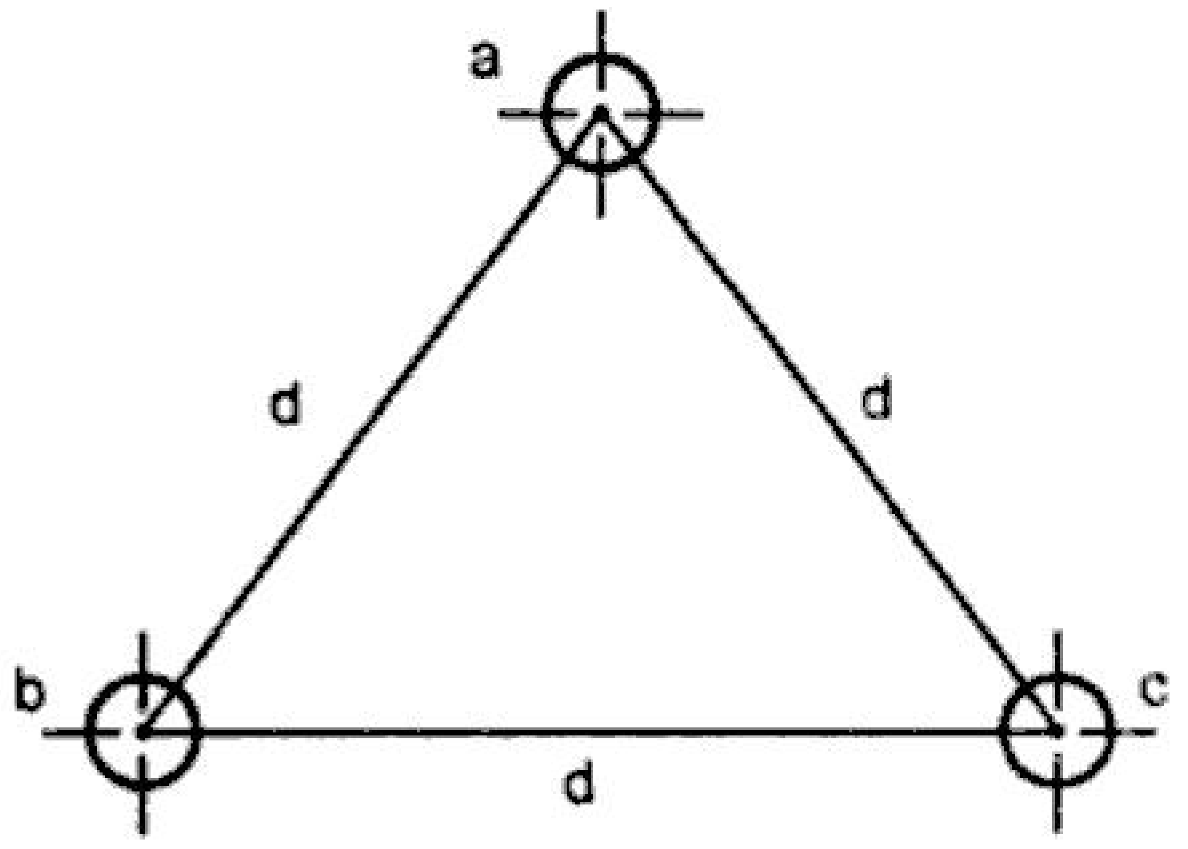


Fig. 2.38

Consider the three conductors a, b and c of 3 phase overhead transmission line having the charges q_a, q_b and q_c respectively as shown in Fig. 2.38. Let the conductors be separated from each other by a distance of d from each other and placed on the vertices of equilateral triangle.

The radius of each conductor is say r. The voltage V_{ab} of the three phase line due to only charges on conductors a and b is given by,

$$V_{ab} = \frac{1}{2\pi\varepsilon}\left(q_a \, ln\frac{d}{r} + q_b ln\frac{r}{d}\right)$$

Voltage V_{ab} due to only charge q_c is zero as uniform charge distribution over the surface of the conductor is equivalent to a concentrated charge at the centre of conductor.

$$\therefore \quad V_{ab} = \frac{q_c}{2\pi\varepsilon} ln\frac{d}{d}$$

Considering all the three charges in writing the voltage equation we have,

$$V_{ab} = \frac{1}{2\pi\varepsilon}\left[q_a \, ln\frac{d}{r} + q_b \, ln\frac{r}{d} + q_c \, ln\frac{d}{d}\right] \quad \text{...(I)}$$

Similarly, $$V_{ac} = \frac{1}{2\pi\varepsilon}\left[q_a \, ln\frac{d}{r} + q_b \, ln\frac{d}{d} + q_c \, ln\frac{r}{d}\right] \quad \text{...(II)}$$

Adding equations (I) and (II),

$$V_{ab} + V_{ac} = \frac{1}{2\pi\varepsilon}\left[2q_a \, ln\frac{d}{r} + (q_b + q_c) ln\frac{r}{d}\right]$$

The voltages are sinusoidal and expressed as the phasors. In absence of other charges in the vicinity the sum of the charges is zero i.e.

$$q_a + q_b + q_c = 0$$

$$\therefore \quad q_b + q_c = -q_a$$

$$V_{ab} + V_{ac} = \frac{1}{2\pi\varepsilon}\left[2q_a \, ln\frac{d}{r} - q_a \, ln\frac{r}{d}\right] = \frac{1}{2\pi\varepsilon}\left[2q_a \, ln\frac{d}{r} + q_a \, ln\frac{d}{r}\right]$$

$$= \frac{3q_a}{2\pi\varepsilon} ln\frac{d}{r}$$

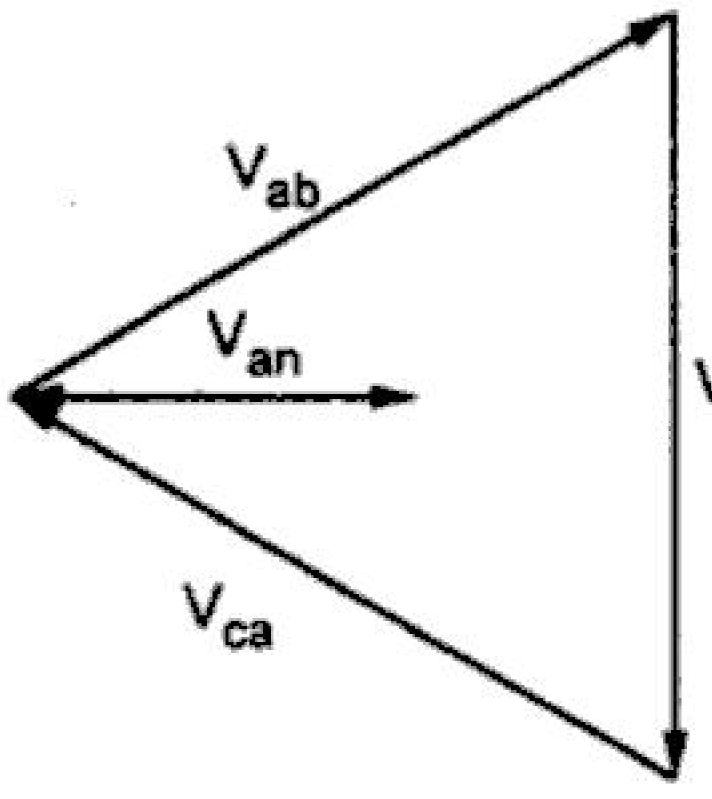


Fig. 2.39

The Fig. 2.39 shows phasor diagram of balanced voltages of three phase line.

$$V_{ab} = \sqrt{3}\, V_{an} \angle 30° = \sqrt{3}\, V_{an} \, [0.866 + j\, 0.5]$$

$$V_{ac} = -V_{ca} = \sqrt{3}\, V_{an} \angle -30°$$

$$= \sqrt{3}\, V_{an} \, [0.866 - j\, 0.5]$$

Adding above equations we get,

$$V_{ab} + V_{ac} = 3\, V_{an}$$

$$3V_{an} = \frac{3q_a}{2\pi\varepsilon} ln\frac{d}{r}$$

$$\therefore \quad V_{an} = \frac{q_a}{2\pi\varepsilon} ln\frac{d}{r}$$

$$C_{an} = \frac{q_a}{V_{an}} = \frac{2\pi\varepsilon}{ln\frac{d}{r}} \text{ F/m} = \frac{2\pi\varepsilon_0\varepsilon_r}{ln\frac{d}{r}} \text{ F/m}$$

For air, $\varepsilon_r = 1$

$$\therefore \quad C_{an} = 2\pi\varepsilon_0 \,/\, ln\frac{d}{r}$$

It can be seen that capacitance to neutral for single phase and equilaterally spaced three phase lines is same.

The current associated with capacitance of a transmission line is termed as **charging** current. In case of single phase circuits, the charging current is the product of line to line voltage and line to line susceptance.

$$I_C = j\omega C_{ab} V_{ab}$$

In case of three phase circuits, the charging current is found by product of voltage to neutral and capacitive susceptance to neutral. The charging current obtained is for one phase. The current in any phase is given by,

$$I_C = j\omega C_n V_{an}$$

The charging current is not same everywhere as the rms voltage along line varies. For obtaining the charging current the value of voltage used is that for which the line is designed which may not be actual voltage at either generating station or a load.

2.26 Capacitance of a Three Phase Line with Unsymmetrical Spacing

The calculation of capacitance in case of conductors in three phase system which are not equally spaced is difficult. If the line is untransposed the capacitances of each phase to neutral is not same.

In case of transposed line the average capacitance of each line to neutral over a complete transposition cycle is same as the average capacitance to neutral of any other phase. Each conductor occupies the same position of every other conductor after equal distance. The effect of unsymmetry between the lines is small and calculations are carried out by considering transposition of lines.

The Fig. 2.40 shows three phase line with unsymmetrical spacing. The radius of each conductor is r.

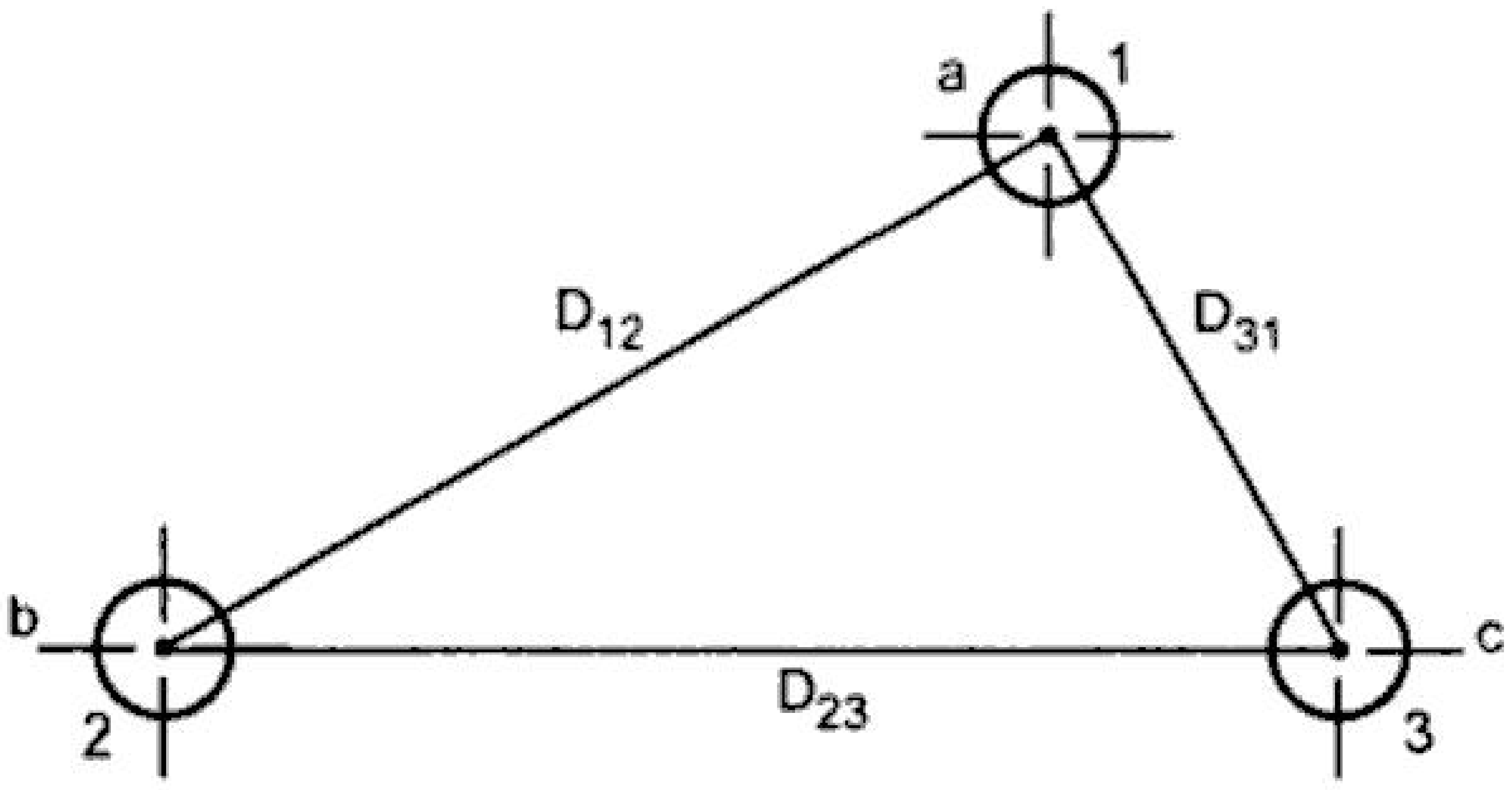


Fig. 2.40

When phase 'a' is in position 1, 'b' in position 2 and 'c' is in position 3.

$$V_{ab_1} = \frac{1}{2\pi\varepsilon}\left(q_a \, ln\frac{D_{12}}{r} + q_b \, ln\frac{r}{D_{12}} + q_c \, ln\frac{D_{23}}{D_{31}}\right)$$

When phase 'a' is in position 2, 'b' in position 3 and 'c' in position 1,

$$V_{ab_2} = \frac{1}{2\pi\varepsilon}\left(q_a \, ln\frac{D_{23}}{r} + q_b \, ln\frac{r}{D_{23}} + q_c \, ln\frac{D_{31}}{D_{12}}\right)$$

When phase 'a' is in position 3, 'b' in position 1 and 'c' in position 2

$$V_{ab_3} = \frac{1}{2\pi\varepsilon}\left(q_a \, ln\frac{D_{31}}{r} + q_b \, ln\frac{r}{D_{31}} + q_c \, ln\frac{D_{12}}{D_{23}}\right)$$

Average voltage between conductors 'a' and 'b' is given by

$$V_{ab} = \frac{V_{ab_1} + V_{ab_2} + V_{ab_3}}{3} = \frac{1}{6\pi\varepsilon}\left(q_a \, ln\frac{D_{12}\,D_{23}\,D_{31}}{r^3} + q_b \, ln\frac{r^3}{D_{12}\,D_{23}\,D_{31}}\right.$$

$$\left. + q_c \, ln\frac{D_{23}\,D_{31}\,D_{12}}{D_{31}\,D_{12}\,D_{23}}\right)$$

$$= \frac{1}{6\pi\varepsilon}\left(q_a \, ln \frac{D_{12}\, D_{23}\, D_{31}}{r^3} + q_b \, ln \frac{r^3}{D_{12}\, D_{23}\, D_{31}} \right)$$

Let $D_{eq} = \sqrt[3]{D_{12}\, D_{23}\, D_{31}}$

$$= \frac{1}{2\pi\varepsilon}\left(q_a \, ln \frac{D_{eq}}{r} + q_b \, ln \frac{r}{D_{eq}} \right)$$

Similarly average voltage drop between a and c is given by,

$$V_{ac} = \frac{1}{2\pi\varepsilon}\left(q_a \, ln \frac{D_{eq}}{r} + q_c \, ln \frac{r}{D_{eq}} \right)$$

We have, $V_{ab} + V_{ac} = 3\, V_{an}$

$$3V_{an} = \frac{1}{2\pi\varepsilon}\left[2q_a \, ln \frac{D_{eq}}{r} + q_b \, ln \frac{r}{D_{eq}} + q_c \, ln \frac{r}{D_{eq}} \right]$$

For balanced circuit $(q_a + q_b + q_c) = 0$.

$$3\, V_{an} = \frac{1}{2\pi\varepsilon}\left[3q_a \, ln \frac{D_{eq}}{r} \right]$$

$$V_{an} = \frac{1}{2\pi\varepsilon} \, q_a \, ln \frac{D_{eq}}{r}$$

$$C_{an} = \frac{q_{an}}{V_{an}} = \frac{2\pi\varepsilon}{ln\left(\frac{D_{eq}}{r}\right)} \text{ F/m}$$

2.27 Effect of Earth on Capacitance of Transmission Line

The capacitance of transmission line is affected by the presence of earth. Because of earth, electric field of a line is reduced. If we assume that the earth is a perfect conductor in the form of a horizontal plane of infinite extent, we realize that the electric field of charged conductors above the earth is not the same as it would be if the equipotential surface of earth were not present.

The method of images is used while considering this type of problems. For this consider a single phase line having 2 conductors as shown in the Fig. 2.41.

A fictitious conductor is placed below each conductor of the same size and shape as the overhead conductor lying directly below the original conductor at a distance equal to twice the distance of the conductor above the plane of ground. If the earth is removed and a charge equal and opposite to that an overhead conductor is assumed on the fictitious conductor, the plane midway between conductor and its image is an equipotential surface and occupies the same position as the equipotential surface of earth. This fictitious conductor is called image conductor having the charge opposite to that of overhead conductor.

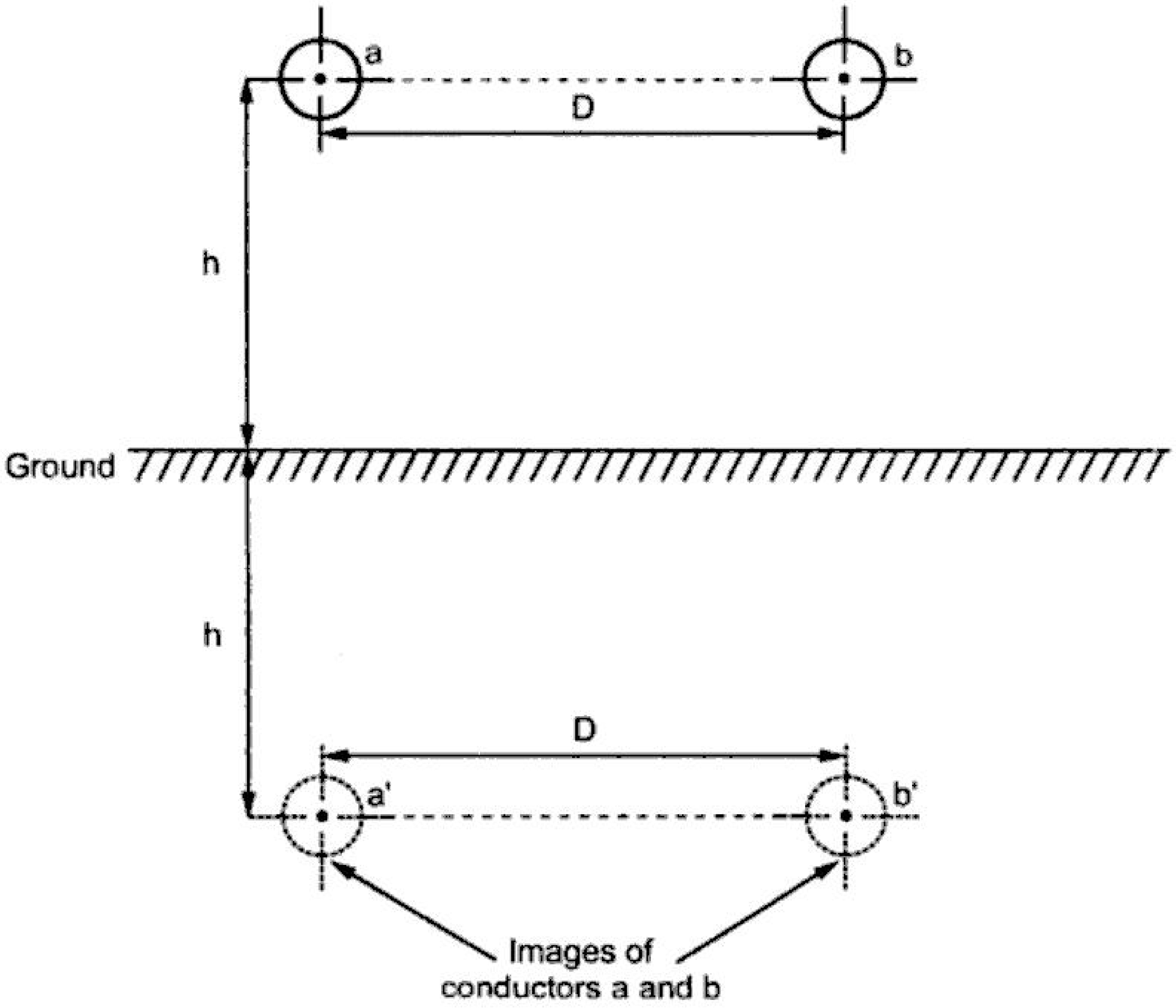


Fig. 2.41

The voltage V_{ab} is given as,

$$V_{ab} = \frac{1}{2\pi\varepsilon}\left\{q_a \, ln\frac{D}{r} + q_b \, ln\frac{r}{D}\right\} + \frac{1}{2\pi\varepsilon}\left\{-q_a \, ln\frac{\sqrt{D^2+4h^2}}{2h} - q_b \, ln\frac{2h}{\sqrt{D^2+4h^2}}\right\}$$

$$= \frac{1}{2\pi\varepsilon}\left\{q_a \, ln\frac{2hD}{r\sqrt{D^2+4h^2}} + q_b \, ln\frac{r\sqrt{D^2+4h^2}}{2hD}\right\}$$

But $q_b = -q_a$

$$= \frac{1}{2\pi\varepsilon}\left\{q_a \, ln\frac{2hD}{r\sqrt{D^2+4h^2}} - q_a \, ln\frac{r\sqrt{D^2+4h^2}}{2hD}\right\}$$

$$= \frac{1}{2\pi\varepsilon} q_a \, ln\left[\frac{4h^2D^2}{r^2\,(D^2+4h^2)}\right] = \frac{1}{2\pi\varepsilon} q_a \, ln\left[\frac{D^2}{r^2\left(1+\frac{D^2}{4h^2}\right)}\right]$$

$$= \frac{1}{2\pi\varepsilon} 2q_a \, ln\left[\frac{D}{r\sqrt{r^2\left(1+\frac{D^2}{4h^2}\right)}}\right] = \frac{1}{\pi\varepsilon} q_a \, ln\left[\frac{D}{r\sqrt{1+\frac{D^2}{4h^2}}}\right]$$

$$C_{ab} = \frac{q_a}{V_{ab}} = \frac{\pi\varepsilon}{ln\left[\frac{D}{r\sqrt{1-\frac{D^2}{4h^2}}}\right]}$$

Comparing above equation with expression for capacitance of single phase line without considering the effect of earth, we can see that earth tries to increase the capacitance of line by small amount. But the effect is negligible if the conductors are high above ground compared to distances between them.

2.28 Bundled Conductors

The Fig. 2.42 shows the arrangement if the conductors are bundled one.

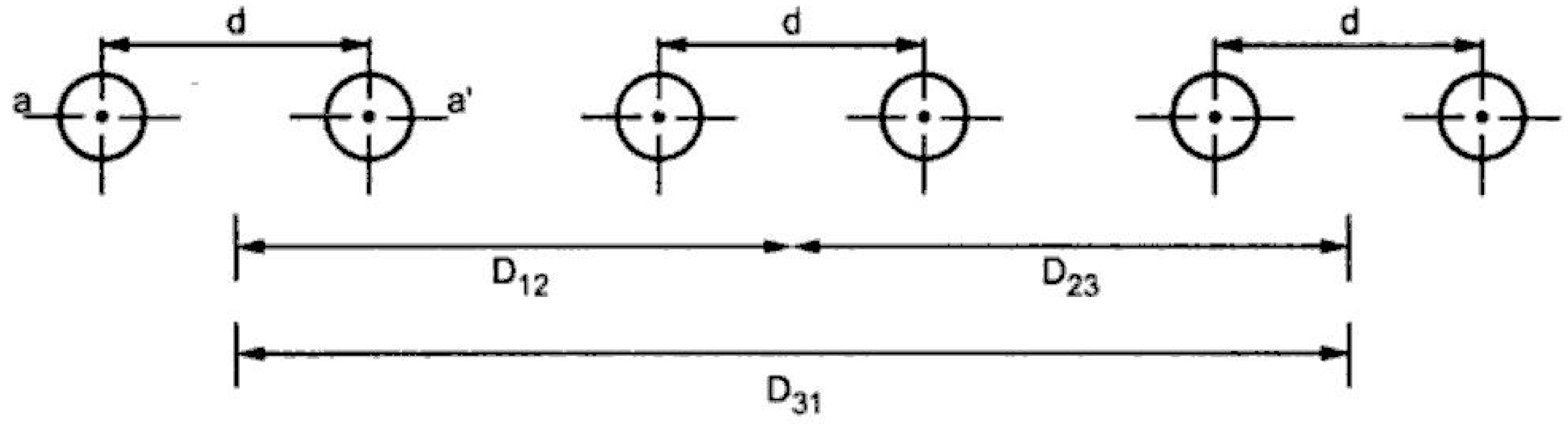


Fig. 2.42

The conductors of any one bundle are in parallel and charge per bundle is assumed to divide equally between the conductors of bundle.

The composite or stranded conductors touch each other while the bundled conductors are away from each other. The typical distance is about 30 cm and more. The conductors of each phase are connected by using connecting wires at particular length.

Due to excessive corona loss, the round conductors are not feasible for use for voltage level more than 230 kV. It is preferable to use hollow conductor in substations while bundled conductors in transmission lines.

Following are advantages of bundled conductors.

1. Low radio interference and corona loss.
2. Reduced voltage gradiant at conductor surface.
3. Increase in capacitance.
4. Low reactance due to increase in self GMD.
6. Increase in surge impedance loading.

If the charge on phase a is q_a then charge on each of the conductors a and a′ will be $q_a/2$. Same is the case with remaining two phases.

$$V_{ab} = \frac{1}{2\pi\varepsilon}\left[\frac{q_a}{2}\left(ln\frac{D_{12}}{r}+ln\frac{D_{12}}{d}\right)+\frac{q_b}{2}\left(ln\frac{r}{D_{12}}+ln\frac{d}{D_{12}}\right)+\frac{q_c}{2}\left(ln\frac{D_{23}}{D_{31}}+ln\frac{D_{23}}{D_{31}}\right)\right]$$

$$V_{ab} = \frac{1}{2\pi\varepsilon}\left\{q_a \cdot ln\left[\frac{D_{12}}{\sqrt{r\,d}}\right]+q_b\, ln\cdot\left[\frac{\sqrt{r\,d}}{D_{12}}\right]+q_c\, ln\left[\frac{D_{23}}{D_{31}}\right]\right\}$$

This equation is similar to the expression we have written for 3 phase line with unsymmetrical spacing. Combining the terms we get

$$C_{an} = \frac{2\pi\varepsilon}{ln\left[D_{eq}/\sqrt{rd}\right]} = \frac{2\pi\varepsilon}{ln\left[D_{eq}/D_{sc}^{b}\right]}$$

Here, $D_{sc}^{b} = \sqrt{rd}$ = Modified GMR for capacitor

Thus, for a two strand bundle

$$D_{sc}^{b} = \sqrt[4]{(r\times d)^2} = \sqrt{rd}$$

For a three strand bundle

$$D_{sc}^{b} = \sqrt[9]{(r\times d\times d)^3} = \sqrt[3]{rd^2}$$

2.28.1 Stranded Conductor

The stranded conductor usually has a central wire which is surrounded by the layers of wires. These layers consists of 6, 12, 18, ... wires successively. Thus the total strands are 7, 13, 19 ....

Such a stranded conductor with 37 strands is shown in the Fig. 2.43.

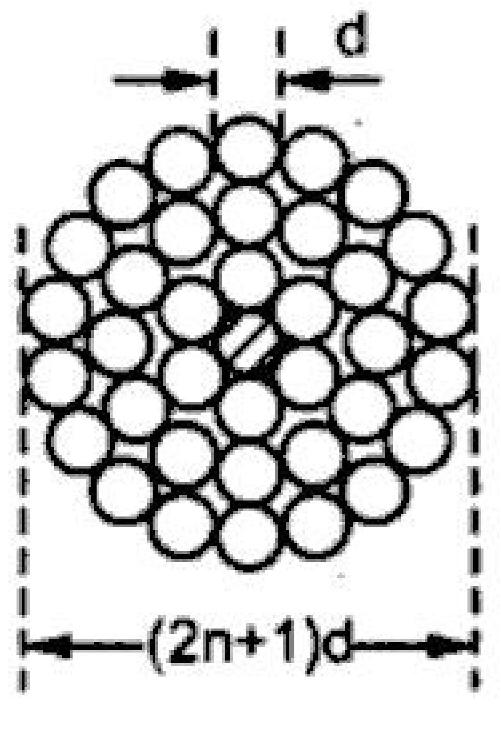


Fig. 2.43

Let d = Diameter of each strand

Then the total diameter of a stranded conductor (cable) is given by,

$$d_c = (2n + 1)\, d$$

where n = Number of layers in which the strands are arranged around central strand.

The stranded conductor is specified as number of strands and diameter of strand.

For example 7/0.295 mm which indicates 7 strands with 0.295 mm diameter of each strand.

If at all the number of layers are not specified then the number of layers can be calculated as number of strands and layers are related to each other by the equation,

$$x = 3n^2 + 3n + 1$$

where x = Number of strands

and n = Number of layers

The standard number of strands in each successive layer from inner to outer is 6, 12, 18, 24 ....

2.29 Capacitance of Three Phase Line with more than One Circuit

Consider the arrangement of conductors shown in the Fig. 2.44.

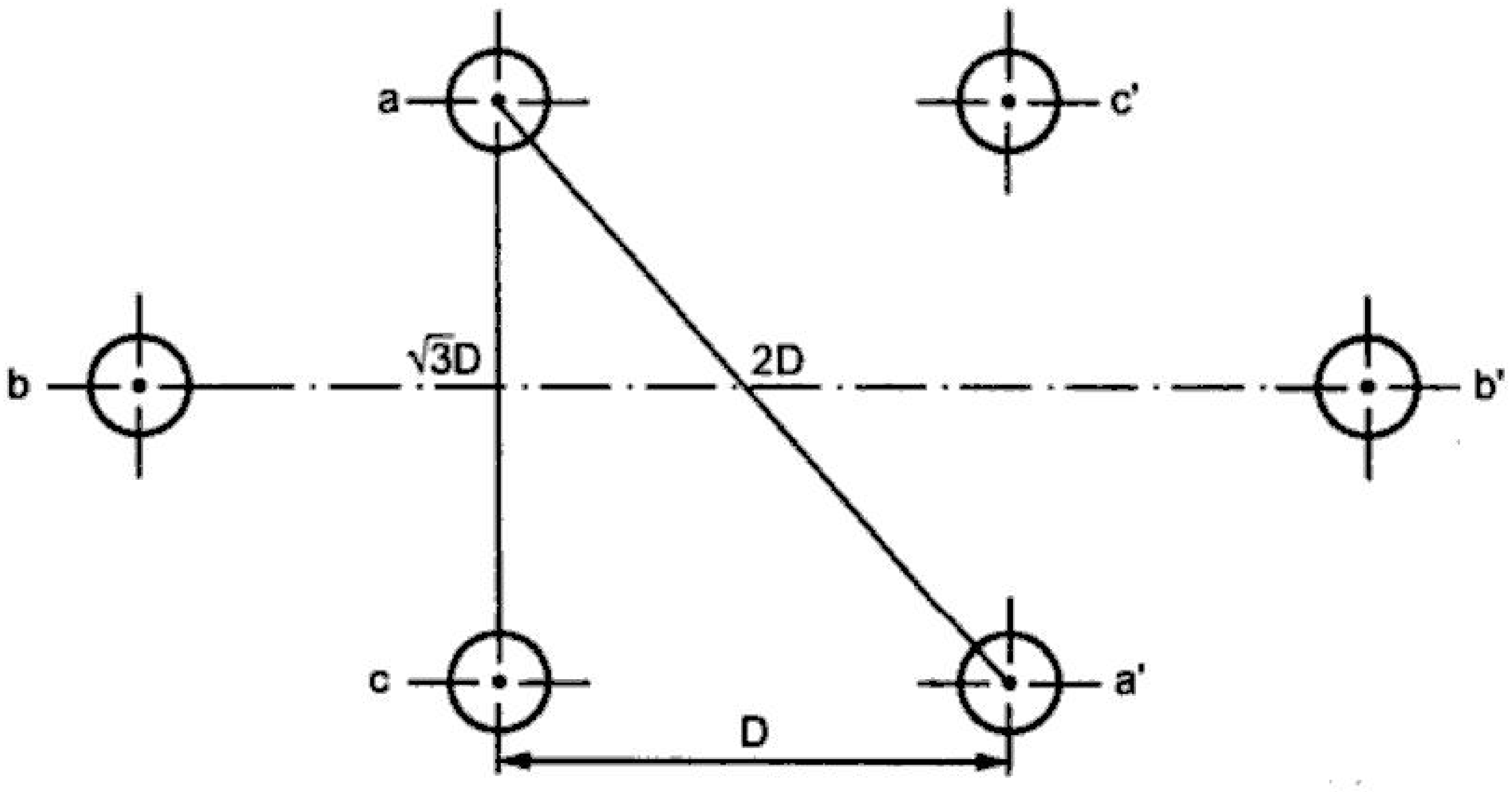


Fig. 2.44

The voltage between phases a and b is given by,

$$V_{ab} = \frac{1}{2\pi\varepsilon}\left\{\begin{array}{l} q_a\left[ln\left(\frac{D}{r}\right)+ln\left(\frac{\sqrt{3}\,D}{2D}\right)\right]+q_b\left[ln\left(\frac{r}{D}\right)+ln\left(\frac{2D}{\sqrt{3}\,D}\right)\right] \\ +q_c\left[ln\left(\frac{D}{\sqrt{3}\,D}\right)+ln\left(\frac{\sqrt{3}\,D}{D}\right)\right]\end{array}\right\}$$

$$= \frac{1}{2\pi\varepsilon}\left\{q_a\left(ln\frac{\sqrt{3}\,D}{2r}\right)+q_b\left(ln\frac{2r}{\sqrt{3}\,D}\right)+q_c\,ln\left(\frac{\sqrt{3}\,D^2}{\sqrt{3}\,D^2}\right)\right\}$$

$$= \frac{1}{2\pi\varepsilon}\left\{q_a\,ln\frac{\sqrt{3}\,D}{2r}+q_b\,ln\frac{2r}{\sqrt{3}\,D}\right\}$$

Similarly,

$$V_{ac} = \frac{1}{2\pi\varepsilon}\left\{q_a\,ln\frac{\sqrt{3}\,D}{2r}+q_c\,ln\frac{2r}{\sqrt{3}\,D}\right\}$$

We have, $V_{ab} + V_{ac} = 3\,V_{an}$

$$3\,V_{an} = \frac{1}{2\pi\varepsilon}\left\{2q_a\,ln\frac{\sqrt{3}\,D}{2r}+(q_b+q_c)\,ln\frac{2r}{\sqrt{3}\,D}\right\}$$

$$q_a + q_b + q_c = 0$$

$$\therefore \quad q_b + q_c = -q_a$$

$$3V_{an} = \frac{1}{2\pi\varepsilon}\left\{2q_a\,\frac{\sqrt{3}\,D}{2r}-(-q_a)\,ln\frac{\sqrt{3}\,D}{2r}\right\}$$

$$3\,V_{an} = \frac{1}{2\pi\varepsilon}\cdot 3q_a\,ln\frac{\sqrt{3}\,D}{2r}$$

$$\therefore \quad V_{an} = \frac{q_a}{2\pi\varepsilon}\,ln\frac{\sqrt{3}\,D}{2r}$$

$$\therefore \quad C_{an} = \frac{q_a}{V_{an}} = \frac{2\pi\varepsilon}{ln\left(\frac{\sqrt{3}\,D}{2r}\right)}$$

Capacitance per phase will be nothing but 2 C_{an}.

2.30 Capacitance of Three Phase Double Circuit with Unsymmetrical Spacing but Transposed

Consider the arrangement of conductors shown in the Fig. 2.45. It consists of three phase double circuit. The radius of each conductor r.

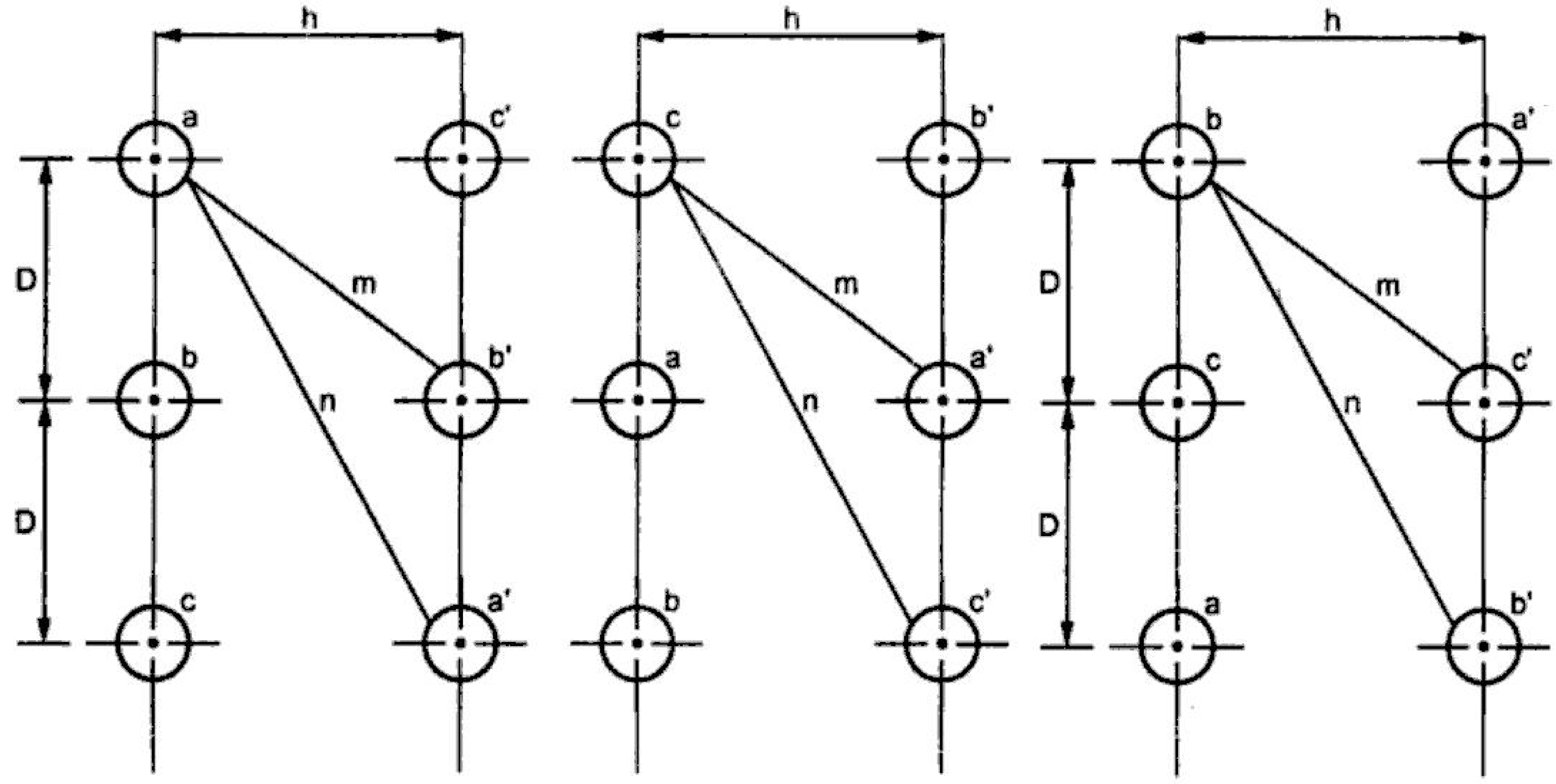


Fig. 2.45

The voltage between phases a and b can be calculated in order to calculate capacitance. One complete cycle of transposition is shown in the Fig. 2.45.

$$V_{ab1} = \frac{1}{2\pi\varepsilon}\left\{q_a\left(ln\frac{D}{r}+ln\frac{m}{n}\right)+q_b\left(ln\frac{r}{D}+ln\frac{h}{m}\right)+q_c\left(ln\frac{D}{2D}+ln\frac{m}{h}\right)\right\}$$

$$V_{ab2} = \frac{1}{2\pi\varepsilon}\left\{q_a\left(ln\frac{D}{r}+ln\frac{m}{h}\right)+q_b\left(ln\frac{r}{D}+ln\frac{h}{m}\right)+q_c\left(ln\frac{2D}{D}+ln\frac{h}{m}\right)\right\}$$

$$V_{ab3} = \frac{1}{2\pi\varepsilon}\left\{q_a\left(ln\frac{2D}{r}+ln\frac{h}{n}\right)+q_b\left(ln\frac{r}{2D}+ln\frac{n}{h}\right)+q_c\left(ln\frac{D}{D}+ln\frac{m}{m}\right)\right\}$$

$$V_{ab} = \frac{1}{3}\left[V_{ab1}+V_{ab2}+V_{ab3}\right]$$

$$= \frac{1}{6\pi\varepsilon}\left\{q_a\left(ln\frac{2D^3}{r^3}+ln\frac{m^2h}{n^2h}\right)+q_b\left(ln\frac{r^3}{2D^3}+ln\frac{n^2h}{m^2h}\right)+q_c\left(ln\frac{2D^3}{2D^3}+ln\frac{m^2h}{m^2h}\right)\right\}$$

$$V_{ab} = \frac{1}{6\pi\varepsilon}\left\{q_a\,ln\frac{2D^3m^2}{r^3n^2}+q_b\,ln\frac{r^3n^2}{2D^3m^2}\right\}$$

Similarly,

$$V_{ac} = \frac{1}{6\pi\varepsilon}\left\{q_a\,ln\frac{2D^3m^2}{r^3n^2}+q_c\,ln\frac{r^3n^2}{2D^3m^2}\right\}$$

We have, $V_{ab} + V_{ac} = 3\ V_{an}$

$$\therefore \quad 3\,V_{an} = \frac{1}{6\pi\varepsilon}\left\{2q_a\, ln\frac{2\,D^3 m^2}{r^3\, n^2} + (q_b + q_c)\, ln\frac{r^3 n^2}{2\,D^3 m^2}\right\}$$

Also, $q_a + q_b + q_c = 0$

$$3\,V_{an} = \frac{1}{6\pi\varepsilon}\left\{3q_a\, ln\frac{2\,D^3 m^2}{r^3\, n^2}\right\}$$

$$V_{an} = \frac{1}{6\pi\varepsilon}\left\{q_a\, ln\frac{2\,D^3 m^2}{r^3 n^2}\right\}$$

$$C_{an} = \frac{q_a}{V_{an}} = \frac{6\pi\varepsilon}{ln\dfrac{2\,D^3 m^2}{r^3 n^2}}$$

$$\therefore \quad C_{an} = \frac{2\pi\varepsilon}{ln\left\{2^{1/3}\left(\dfrac{D}{r}\right)\left(\dfrac{m}{n}\right)^{\frac{2}{3}}\right\}}$$

The capacitance per phase will be 2 C_{an}.

2.31 Skin Effect

When a conductor carries a steady or d.c. current, this current is uniformly distributed over the whole cross-section of the conductor. However the current distribution is non-uniform if conductor carries alternating current. The current density is higher at the surface than at its centre. Thus the current is concentrated near the surface of the conductor as shown in the Fig. 2.46. This effect becomes predominant with increase in frequency. This behaviour of alternating current to concentrate near the surface of the conductor is known as skin effect.

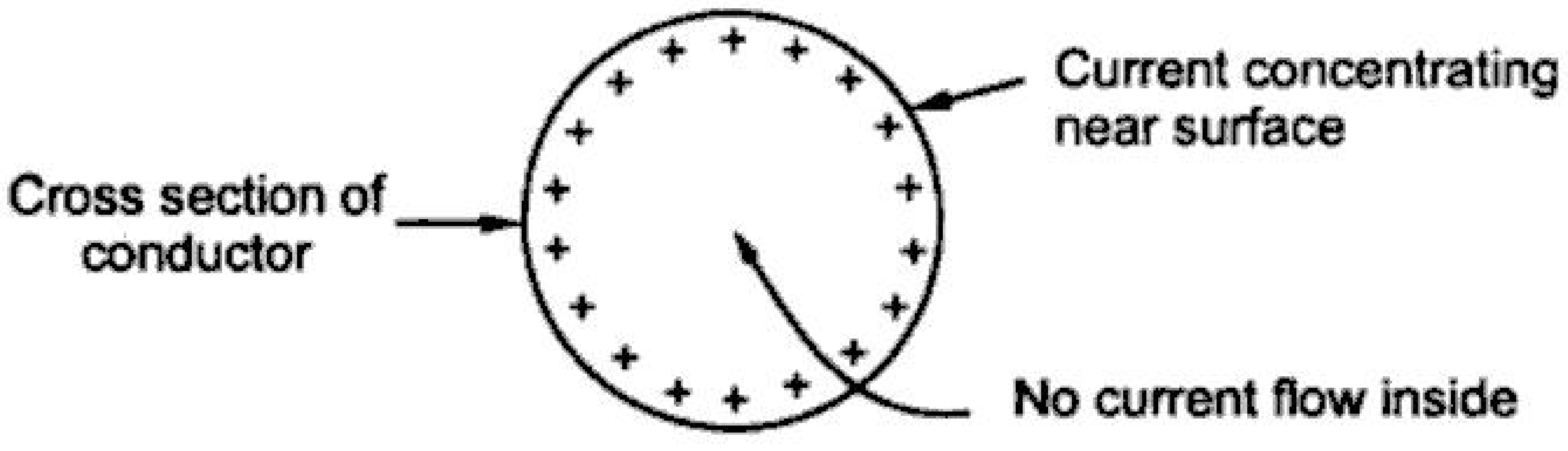

Current concentrating near surface
Cross section of conductor
No current flow inside

Fig. 2.46

Because of skin effect, larger power loss is caused for a given rms value of A.C. than the loss when the same value of DC is flowing through the conductor. Alternatively the effective resistance of conductor is more for A.C. than for D.C.

Due to this skin effect, the effective cross sectional area offered to the flow of current decreases which increases resistance.

Consider a solid, round conductor consisting of large number of strands. Each strand is carrying a small part of current. The strands near the centre are surrounded by a greater magnetic flux and hence have large inductance than that near the surface. As we move towards the outer strands, the flux linking progressively reduces for the reason that the flux inside the strand does not link it. The reactance of inner strands is greater than outer strands which causes the alternating current to flow near the surface of the conductor. With increase in the frequency, the inductive reactance of the strands becomes more and more non-uniform which leads to non-uniform current distribution.

The skin effect is quite significant for large, solid conductors even at a frequency of 50 Hz.

The skin effect depends on following factors :

1. Nature of material
2. Diameter of wire
3. Frequency of supply
4. Shape of wire.

With increase in diameter of wire, the skin effect increases. Similarly as frequency increases, the skin effect increases. If we have stranded conductor rather than solid conductor then the skin effect is less. It can be seen that when supply frequency is less than 50 Hz and conductor diameter is less than 1 cm then skin effect is negligible. In large conductors at power frequencies the skin effect is a significant factor.

2.32 Proximity Effect

The current distribution may be non-uniform because of another effect known as proximity effect.

Consider a two wire line as shown in the Fig. 2.47.

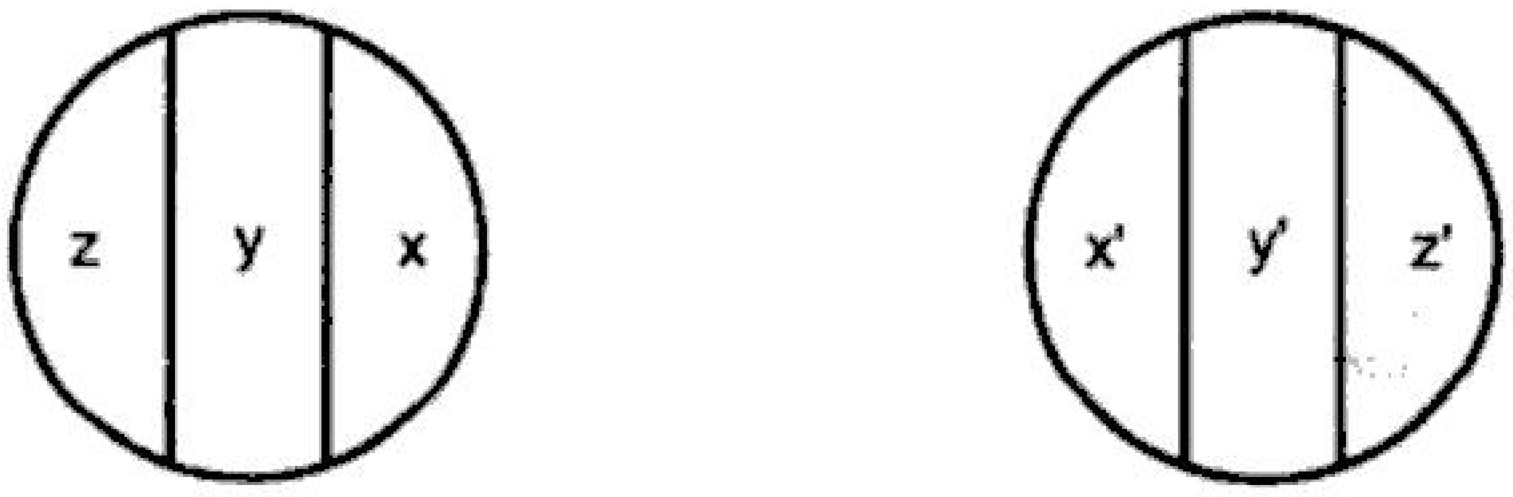


Fig. 2.47

Let each of the line conductor is assumed to be divided into 3 sections having equal cross sectional area. Three parallel loops are formed by the pairs xx′, yy′ and zz′. The flux linking loop xx′ is least and it increases for the remaining loops. Thus the inductance of inner loop is less. Thus the current density is highest at inner edges of the conductor. Due to this non-uniform distribution of current, the effective conductor resistance increases. As the distance between the conductors goes on reducing, this distribution of current becomes more and more non-uniform.

For normal spacing of overhead lines this proximity effect is negligible. For underground cables this effect is significant as the conductors are located close to each other.

The proximity effect also depends on the same factors as that of skin effect.

2.33 Inductive Interference with Neighbouring Circuits

In practice it is observed that the power lines and the communication lines run along the same path. Sometimes it can also be seen that both these lines run on same supports along the same route. The transmission lines transmit bulk power with relatively high voltage. Electromagnetic and electrostatic fields are produced by these lines having sufficient magnitude. Because of these fields, voltages and currents are induced in the neighbouring communication lines. Thus it gives rise to interference of power line with communication circuit.

Due to electromagnetic effect, currents are induced which is superimposed on speech current of the neighbouring communication line which results into distrorion. The potential of the communication circuit as a whole is raised because of electrostatic effect and the communication apparatus and the equipments may get damaged due to extraneous voltages. In the worst situation, the faithful transmission of message becomes impossible due to effect of these fields. Also the potential of the apparatus is raised above the ground to such an extent that the handling of telephone receiver becomes extremely dangerous.

The electromagnetic and the electrostatic effects mainly depend on what is the distance between power and communication circuits and the length of the route over which they are parallel. Thus it can be noted that if the distortion effect and potential rise effect are within permissible limits then the communication will be proper. The unacceptable disturbance which is produced in the telephone communication because of power lines is called Telephone Interference.

There are various factors influencing the telephone interference. These factors are as follows

1) Because of harmonics in power circuit, their frequency range and magnitudes.

2) Electromagnetic coupling between power and telephone conductor.

The electric coupling is in the form of capacitive coupling between power and telephone conductor whereas the magnetic coupling is through space and is generally expressed in terms of mutual inductance at harmonic frequencies.

3) Due to unbalance in power circuits and in telephone circuits.

4) Type of return telephone circuit i.e. either metallic or ground return.

5) Screening effects.

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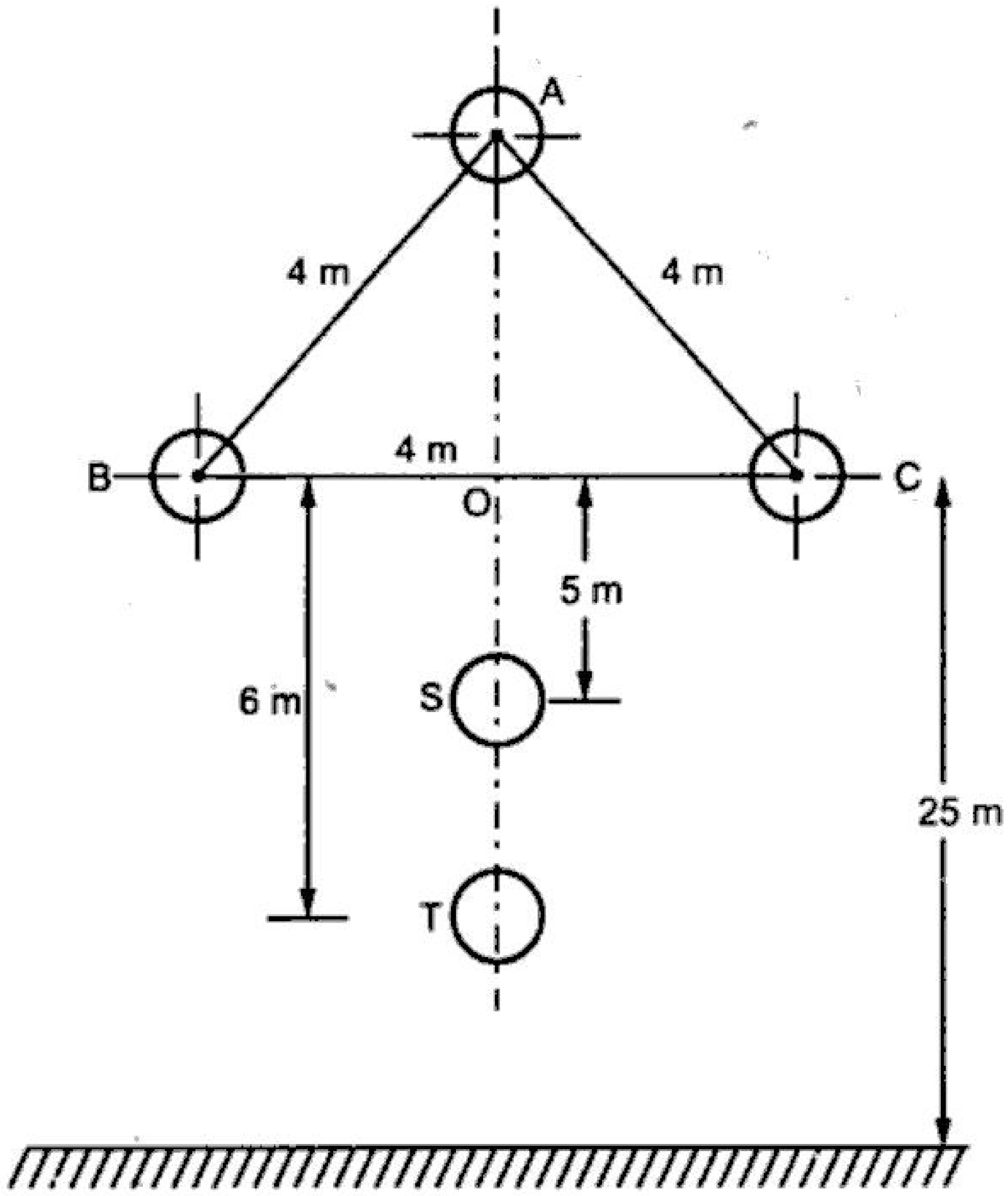

Fig. 2.51

Solution :

$$AO = \sqrt{(4)^2-(2)^2} = \sqrt{16-4} = \sqrt{12} = 3.46 \text{ m}$$

$$AS = AO+OS = 3.46+5 = 8.46 \text{ m}$$

$$AT = AO+OT = 3.46+6 = 9.46 \text{ m}$$

$$BS = \sqrt{(2)^2+(5)^2} = 5.38 \text{ m} = CS$$

$$BT = \sqrt{(2)^2+(6)^2} = 6.32 \text{ m} = CT$$

Now,

$$M_A = 2\times10^{-7}\, ln\frac{AT}{AS} \text{ H/m}$$

$$= 0.2\, ln\frac{AT}{AS} \text{ mH/km}$$

$$= 0.2\, ln\frac{9.46}{8.46} = 0.0223 \text{ mH/km}$$

$$M_B = 2\times10^{-7}\, ln\frac{BT}{BS} \text{ H/m} = 0.2\, ln\frac{BT}{BS} \text{ mH/km}$$

$$= 0.2\, ln\frac{6.32}{5.38}$$

$$= 0.0322 \text{ mH/km} = M_C$$

M_A, M_B and M_C are displaced by 120°

$$M = M_A + M_B + M_C$$

The addition is phasor addition,

$$\begin{aligned} M &= [0.0223 \angle 0°] + [0.0322 \angle -120°] + [0.0322 \angle -240°] \\ &= [0.0223 + j\,0] + [-0.0161 - j\,0.02788] + [-0.0161 + j\,0.02788] \\ &= -9.9 \times 10^{-3} + j\,0 \quad = 9.9 \times 10^{-3} \angle -180° \text{ mH} \end{aligned}$$

Considering only magnitude,

$$M = 9.9 \times 10^{-3} \text{ mH/km} = 9.9\ \mu\text{H/km}$$

$$I_L = \frac{P}{\sqrt{3} \times V_L \times \cos\phi} = \frac{20 \times 10^6}{\sqrt{3} \times 132 \times 10^3 \times 0.8} = 109.34 \text{ A}$$

$$\therefore \quad E_M = 2\pi f M I_L = 2\pi \times 60 \times 9.9 \times 10^{-6} \times 109.34$$

$$= 0.4080 \text{ V/km}$$

$$\therefore \quad E_M = 0.4080 \times 160 = 65.29 \text{ volts}$$

Now,

$$V_{SA} = V_A \frac{ln\left(\frac{2h - AS}{AS}\right)}{ln\left(\frac{2h - r}{r}\right)}$$

But,

$$2h = 2 \times (25 + 3.46) = 56.92 \text{ m}$$

$$\therefore \quad V_{SA} = \frac{132 \times 10^3}{\sqrt{3}} \cdot \frac{ln\left(\frac{56.92 - 8.46}{8.46}\right)}{ln\left(\frac{56.92 - 0.6 \times 10^{-2}}{0.6 \times 10^{-2}}\right)}$$

$$= 76210.23 \times \frac{1.74538}{9.1575} = 14525.28 \text{ volts}$$

$$V_{SB} = V_B \frac{ln\left(\frac{2h' - BS}{BS}\right)}{ln\left(\frac{2h' - r}{r}\right)}$$

$$2h' = 2 \times 25 = 50 \text{ m}$$

Similarly,

$$V_{SB} = \frac{132 \times 10^3}{\sqrt{3}} \frac{ln\left(\frac{50 - 5.38}{5.38}\right)}{ln\left(\frac{50 - 0.6 \times 10^{-2}}{0.6 \times 10^{-2}}\right)}$$

$$= 76210.23 \times \frac{2.1154}{9.0278}$$

$$= 17857.43 \text{ volts} = V_{SC}$$

$$V_S = V_{SA} + V_{SB} + V_{SC}$$

$$= (14525.28 \angle 0°) + (17857.43 \angle -120°) + (17857.43 \angle -240°)$$

$$\therefore \quad V_S = 3332.35 \text{ volts}$$

$$V_{TA} = V_A \frac{ln\left(\frac{2h-AT}{AT}\right)}{ln\left(\frac{2h-r}{r}\right)} = \frac{132\times10^3}{\sqrt{3}} \frac{ln\left(\frac{56.92-9.46}{9.46}\right)}{ln\left(\frac{56.92-0.6\times10^{-2}}{0.6\times10^{-2}}\right)}$$

$$= 76210.23 \times \frac{1.6128}{9.1575} = 13422.11 \text{ volts}$$

$$V_{TB} = V_B \cdot \frac{ln\left(\frac{2h'-BT}{BT}\right)}{ln\left(\frac{2h'-r}{r}\right)}$$

$$= \frac{132\times10^3}{\sqrt{3}} \frac{ln\left(\frac{50-6.32}{6.32}\right)}{ln\left(\frac{50-0.6\times10^{-2}}{0.6\times10^{-2}}\right)}$$

$$\therefore \quad V_{SA} = \frac{132\times10^3}{\sqrt{3}} \frac{ln\left(\frac{56.92-8.46}{8.46}\right)}{ln\left(\frac{56.92-0.6\times10^{-2}}{0.6\times10^{-2}}\right)}$$

$$= 76210.23 \times \frac{1.9331}{9.0278}$$

$$= 16319.30 \text{ volts} = V_{TC}$$

Now, $V_T = V_{TA} + V_{TB} + V_{TC}$

$$= [13422.11 \angle 0°] + [16319.30 \angle -120°] + [16319.30 \angle -240°]$$

$$\therefore \quad V_T = 2897.19 \text{ volts}$$

The potential of points above earth is **3332.35 volts.**

The potential of point T above earth is **2897.19 volts.**

corners of an equilateral triangle or at the corners of right angled triangle for unequal distance between the conductors. The Fig. 2.53 shows various types of arrangements of three phase circuits.

Examples with Solutions

➠ **Example 2.12 :** *A single phase transmission line has two parallel conductors 5 meters apart, radius of each conductor being 1.5 cm. Calculate the capacitance of the line per km. Given that* $\varepsilon_0 = 8.854\times10^{-12}$ *F/m.*

Solution :

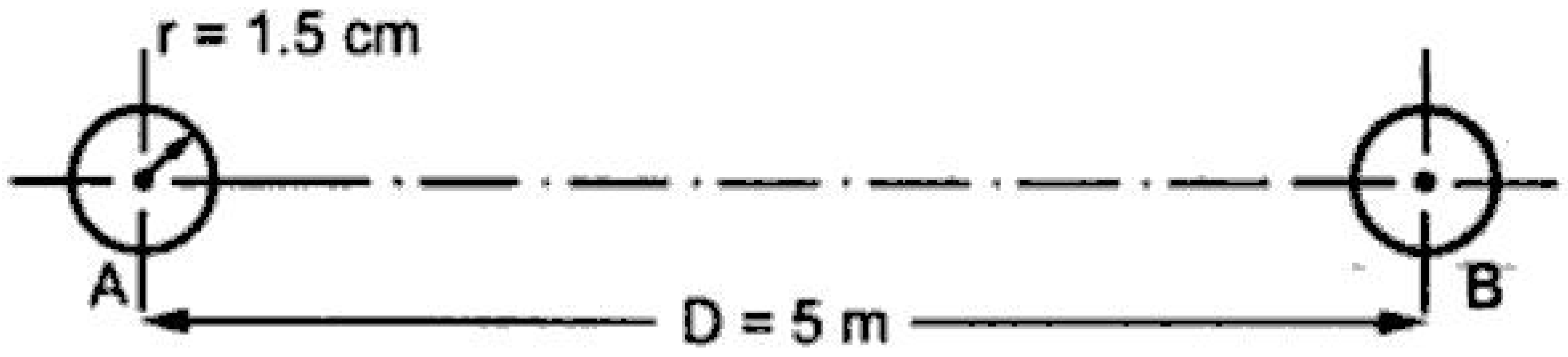

Fig. 2.54

$$r = 1.5 \text{ cm} = 1.5\times10^{-2} \text{ m}, \quad D = 5 \text{ m}$$

$$\varepsilon_0 = 8.854\times10^{-12} \text{ F/m}$$

$$C_{AB} = \frac{\pi\varepsilon}{ln(D/r)} \text{ F/m} = \frac{\pi\varepsilon_0}{ln(D/r)}$$

$$= \frac{\pi(8.854\times10^{-12})}{ln\left(\frac{5}{1.5\times10^{-2}}\right)}\times1000$$

$$\therefore \quad C_{AB} = \mathbf{4.7882\ nF/km}$$

➠ **Example 2.13 :** *Find the capacitance of a single phase line 40 km long consisting of 2 parallel wires each 4 mm in diameter and 2 m apart.*

Determine the capacitance of the same line taking into account effect of ground. The height of conductors above ground is 5 m.

Solution : Neglecting the presence of ground.

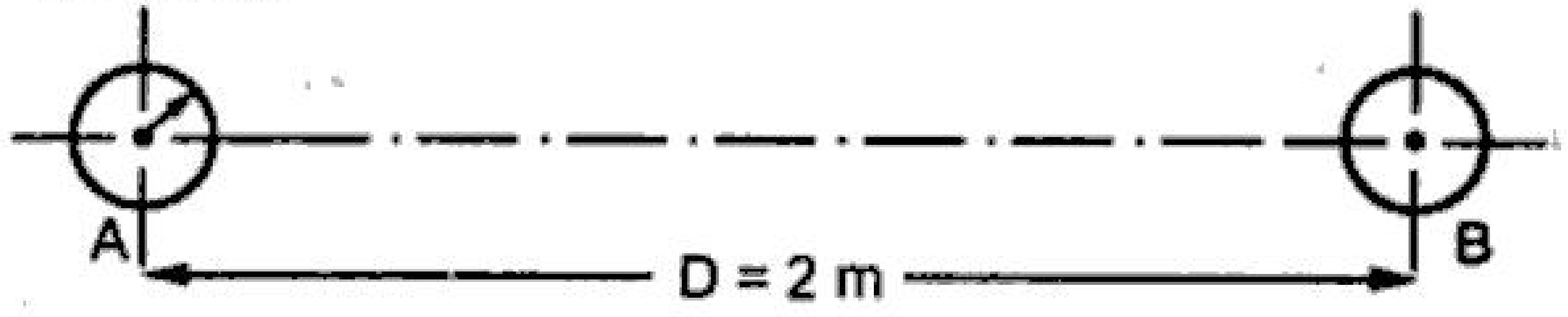

Fig. 2.55

$$\text{Line Length} = 40 \text{ km}$$

$$r = 4 \text{ mm} = 4\times10^{-3} \text{ m}$$

$$D = 2 \text{ m}$$

$$\varepsilon_0 = 8.854\times10^{-12} \text{ F/m}$$

$$C_{AB} = \frac{\pi\varepsilon_0}{ln(D/r)} = \frac{\pi\times 8.854\times10^{-12}}{ln\left(2/4\times10^{-3}\right)} = 4.47585\times10^{-12} \text{ F/m}$$

For line of 40 km length

$$C_{AB} = 4.47585\times10^{-10}\times40\times10^{3}$$

$$= 1.7903\times10^{-7} \text{ F}$$

$$\therefore \quad C_{AB} = 0.17903 \ \mu\text{F}$$

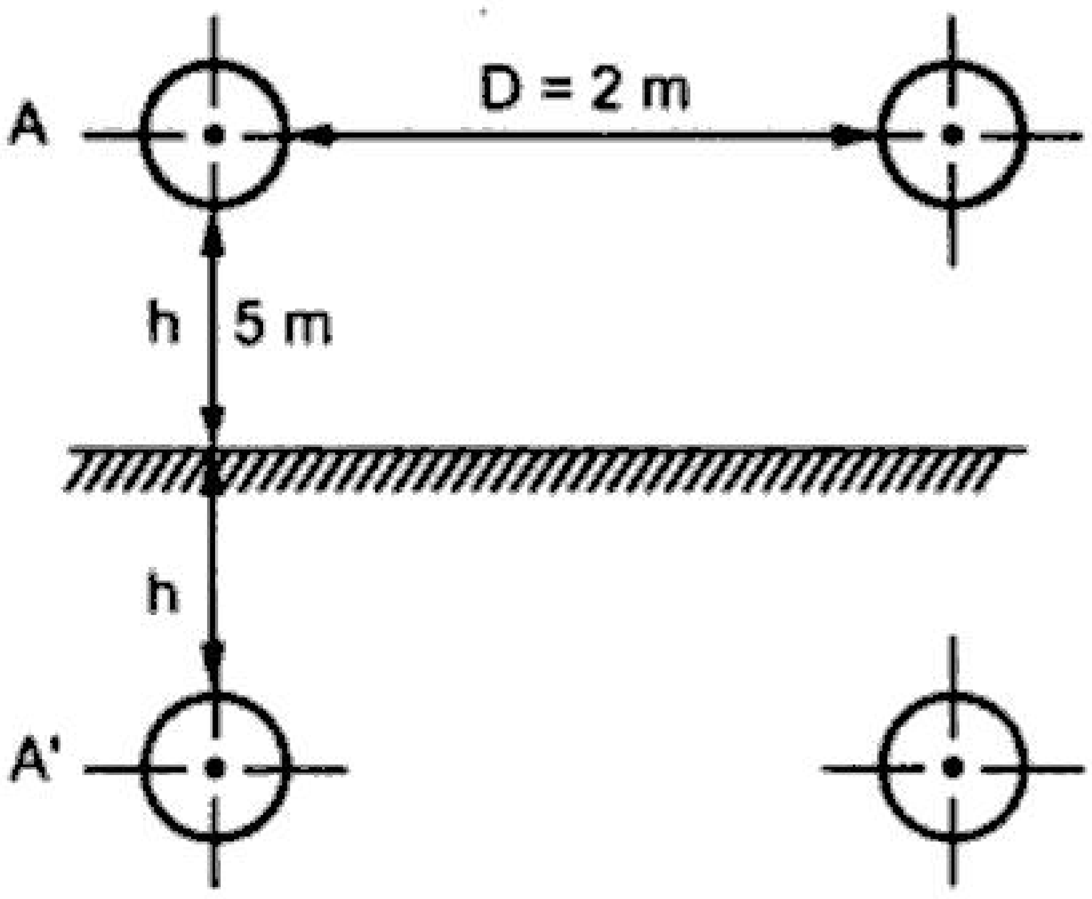

Fig. 2.55 (a)

Considering the presence of ground.

Here,

$\varepsilon_0 = 8.854\times10^{-12}$ F/m

$h = 5$ m

$D = 2$ m

$r = 4 \text{ mm} = 4\times10^{-3}$ m

We have,

$$C_{AB} = \frac{\pi\varepsilon_0}{ln\left[\frac{D}{r\sqrt{1+(D^2/4h^2)}}\right]} \text{ F/m} = \frac{\pi\times8.854\times10^{-12}}{ln\left[\frac{2}{4\times10^{-3}\sqrt{1+[(2)^2/4(5)^2]}}\right]}$$

$$= 4.49\times10^{-12} \text{ F/m}$$

For a line of length of 40 km

$$C_{AB} = 4.49\times10^{-12}\times40\times10^{3} = 1.7960\times10^{-7} \text{ F}$$

$$= \mathbf{0.17960 \ \mu F}$$

Example 2.14 : *A 3 phase, 50 Hz, 66 kV overhead line conductors are placed in a horizontal plane as shown in the Fig. 2.56. The conductor diameter is 1.25 cm. If the line length is 100 km. Calculate i) Capacitance/phase ii) Charging current/phase assuming complete transposition of the line.*

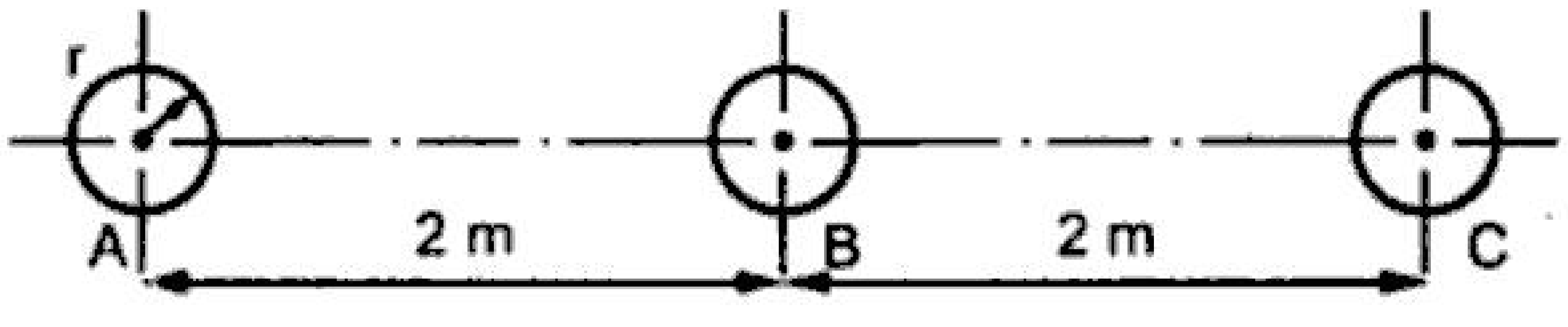

Fig. 2.56

Solution : Equivalent equilateral spacing is given by,

$$d = \sqrt[3]{d_{12}\,d_{23}\,d_{31}} = \sqrt[3]{(2)(2)(4)} = 2.5198 \text{ m}$$

$$r = \frac{1.25}{2}\text{ cm} = \frac{1.25\times10^{-2}}{2}\text{ m} = 6.25\times10^{-3}\text{ m}$$

Line to neutral capacitance is given by,

$$C_{an} = \frac{2\pi\varepsilon_0}{ln\left[\frac{d}{r}\right]}\text{ F/m} = \frac{2\pi\times 8.854\times10^{-12}}{ln[2.5198 / 6.25\times10^{-3}]}$$

$$= 9.2728\times10^{-12}\text{ F/m}$$

For a line length of 100 km,

$$C_{an} = 9.2728\times10^{-12}\times100\times10^{3} = 9.2728\times10^{-7}\text{ F}$$

$$= \mathbf{0.92728\times10^{-6}\text{ F}}$$

The charging current per phase is given by,

$$I_C = \frac{V_{ph}}{X_C} = \frac{66000}{\sqrt{3}}\times2\pi f C$$

$$= \frac{66000}{\sqrt{3}}\times2\pi\times50\times0.92728\times10^{-6}$$

$$\therefore \quad I_C = \mathbf{11.10\text{ A}}$$

Example 2.15 : *Find the capacitance per km per phase to neutral of a three phase line arranged as shown in the Fig. 2.57. The outside diameter of ACSR conductor is 2.50 cm. The line is transposed. Take the effect of ground into consideration.*

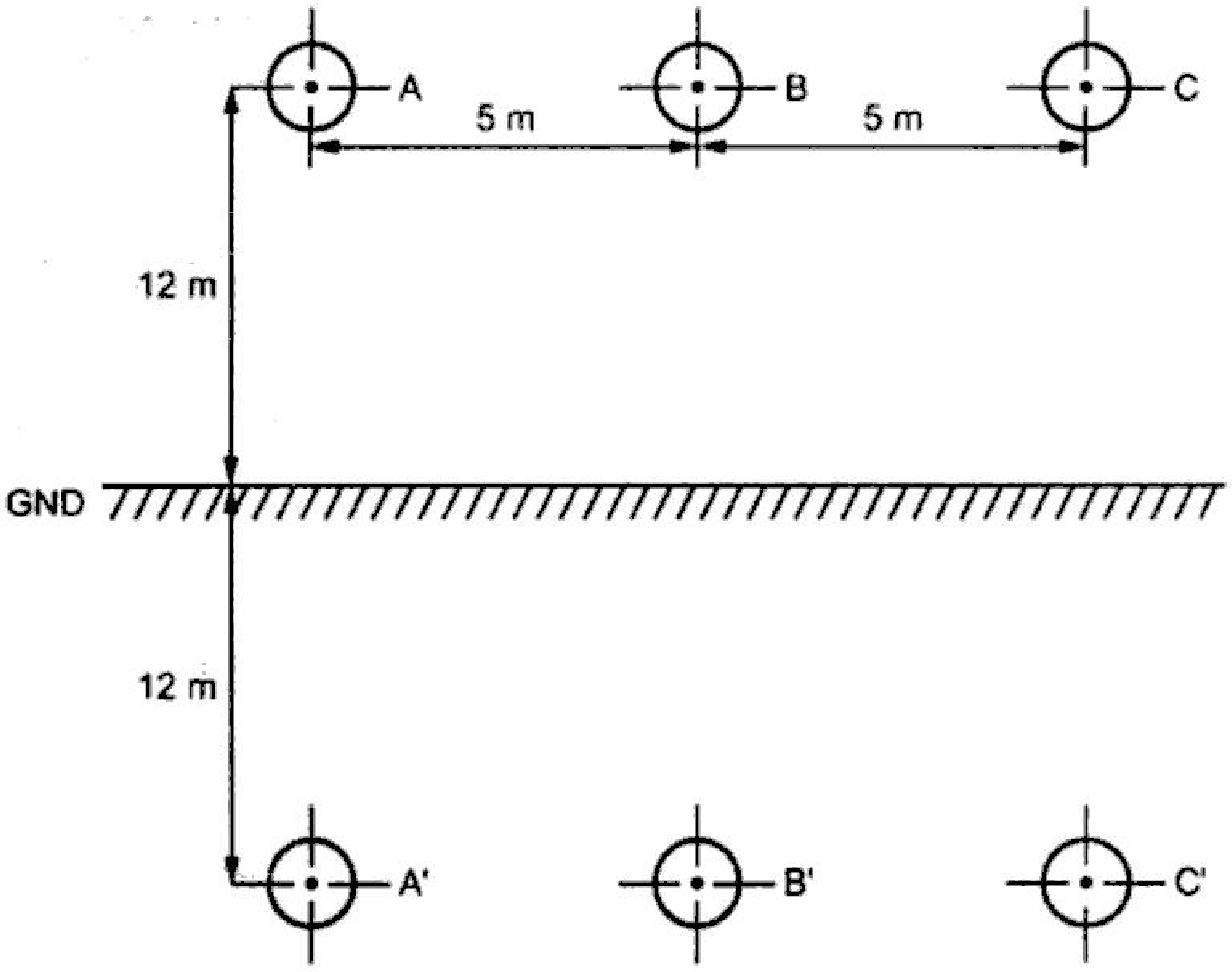

Fig. 2.57

Solution : Here the method of images is to be applied for the calculation of capacitance. Consider the three conductors A, B, C carrying changes q_A, q_B and q_C respectively. The line is transposed. This is shown in the Fig. 2.57 (a).

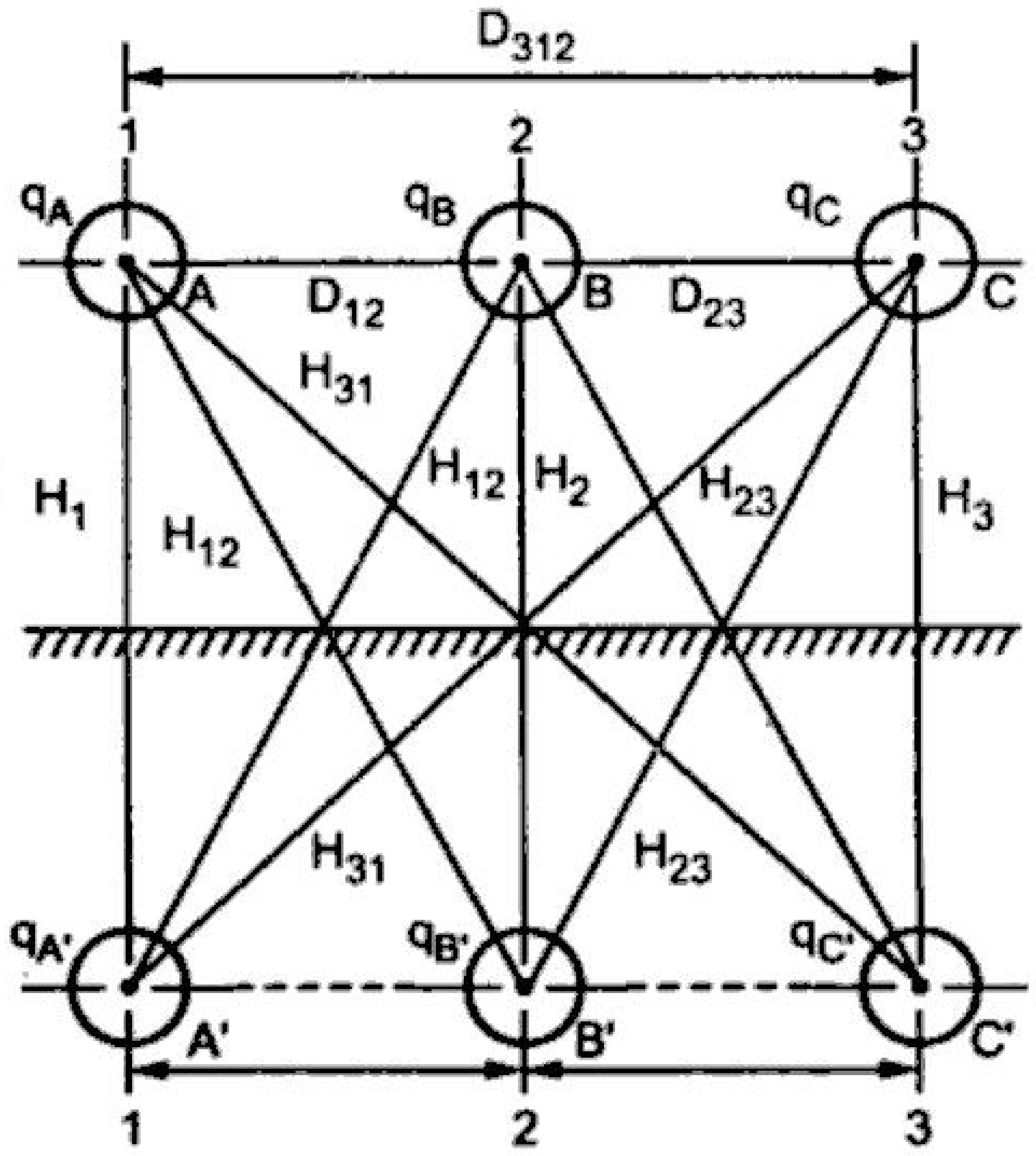

Fig. 2.57 (a)

The plane of the earth is as shown in the Fig. 2.59 below the ground there are image conductors A', B', C' carrying the charges $q_{A'}$, $q_{B'}$ and $q_{C'}$ respectively.

Writing the voltage drop V_{AB} for a complete transposition cycle. Similar equation can be written for voltage drop V_{AC} and then using $V_{AB} + V_{AC} = 3\ V_{AN}$ the capacitance to neutral value can be obtained.

With conductor A in position 1, B in position 2, C in position 3 we have

$$V_{AB_1} = \frac{1}{2\pi\varepsilon}\left\{q_A\left(ln\frac{D_{12}}{r} - ln\frac{H_{12}}{H_1}\right) + q_B\left(ln\frac{r}{D_{12}} - ln\frac{H_2}{H_{12}}\right) + q_C\left(ln\frac{D_{23}}{D_{31}} - ln\frac{H_{23}}{H_{31}}\right)\right\}$$

Similar equations for V_{AB} are written for the other parts of the transposition cycle.

Simplifying the equations as explained earlier we get,

$$C_n = \frac{2\pi\varepsilon_0}{ln(d_{eq} / r) - ln\left(\sqrt[3]{H_{12}H_{23}H_{31}} / \sqrt[3]{H_1H_2H_3}\right)}$$

For the given problem

$$H_1 = 24 \text{ m} = H_2 = H_3$$

$$H_{12} = \sqrt{(24)^2 + (5)^2}$$

$$= 24.51 \text{ m} = H_{23}$$

$$H_{31} = \sqrt{(24)^2 + (10)^2} = 26 \text{ m}$$

$$D_{eq} = \sqrt[3]{D_{12}D_{23}D_{31}}$$

$$= \sqrt[3]{(5)(5)(10)} = 6.2996 \text{ m}$$

$$r = 2.50 \text{ cm} = 2.5 \times 10^{-2} \text{ m}$$

$$C_n = \frac{2\pi \times 8.854 \times 10^{-12}}{ln\left[\frac{6.2996}{2.50 \times 10^{-2}}\right] - ln\left[\frac{\sqrt[3]{(24.51)(24.51)(26)}}{\sqrt[3]{(24)(24)(24)}}\right]}$$

$$= \frac{2\pi \times 8.854 \times 10^{-12}}{5.5293 - 0.04069}$$

$$= 1.0135 \times 10^{-11} \text{ F/m}$$

$$\text{Capacitance per phase per km} = 1.01 \times 10^{-11} \times 10^3$$

$$= 1.0135 \times 10^{-8} \text{ F/km}$$

$$\therefore \quad \mathbf{C_n = 10.135\ nF/km}$$

➡ **Example 2.16 :** *A 3 phase double circuit line is shown in the Fig. 2.58. Find the capacitance per phase to neutral. Diameter of each conductor is 2 cm.*

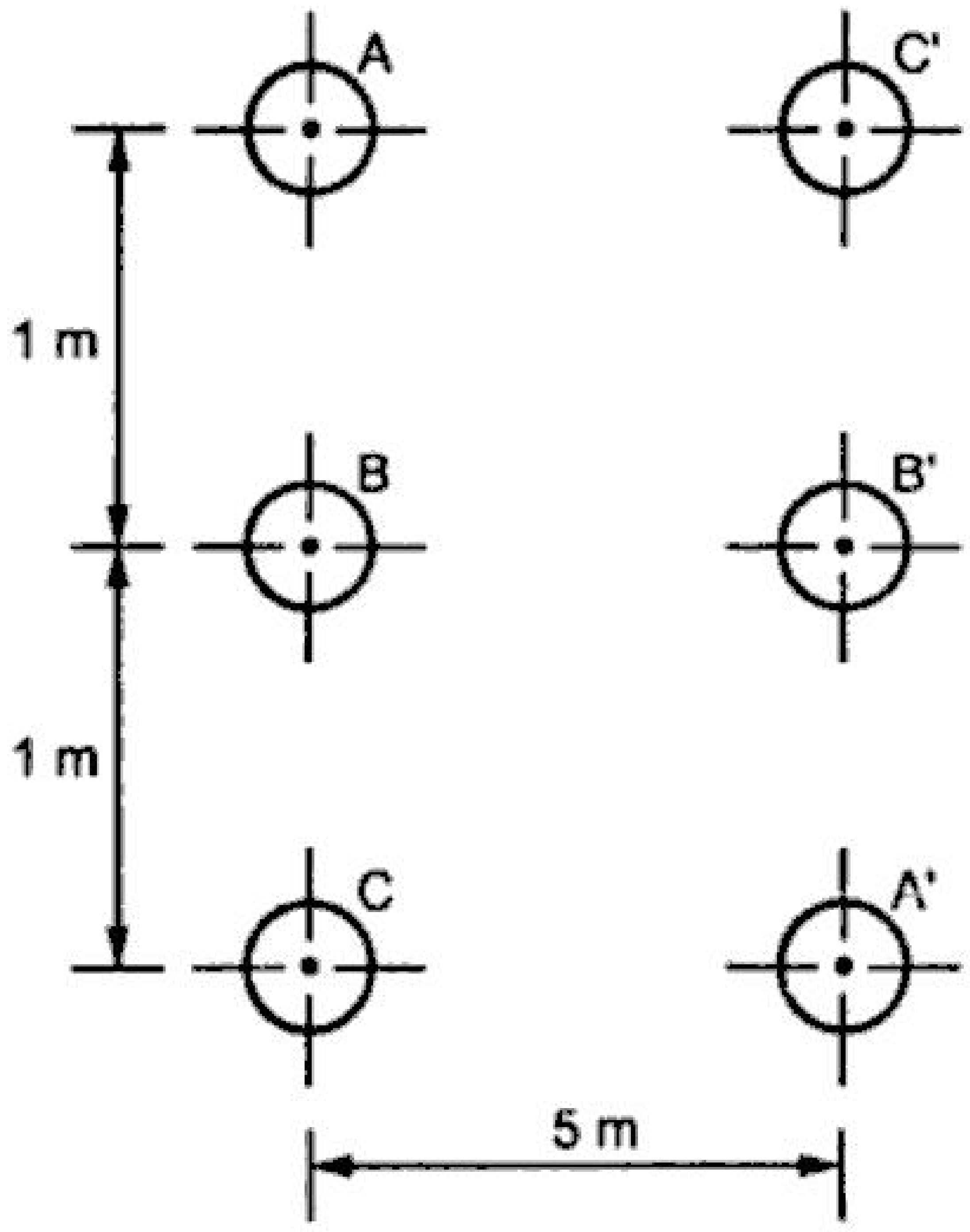

Fig. 2.58

Solution : Here, D = 1 m, r = 2 cm = 0.02 m.

$$h = 5 \text{ m}$$

$$m = \sqrt{D^2 + h^2} = \sqrt{(1)^2 + (5)^2} = \sqrt{26} \text{ m}$$

$$n = \sqrt{(2D)^2 + h^2} = \sqrt{(2)^2 + (5)^2} = \sqrt{29} \text{ m}$$

The capacitance per phase to neutral is given by,

$$C_{an} = 2 \times \frac{2\pi\varepsilon_0}{ln\left\{2^{1/3}\left(\frac{D}{r}\right)\left(\frac{m}{n}\right)^{2/3}\right\}}$$

$$C_{an} = \frac{4\pi\varepsilon_0}{ln\left\{2^{1/3}\left(\frac{D}{r}\right)\left(\frac{m}{n}\right)^{2/3}\right\}}$$

$$= \frac{4\pi \times 8.854 \times 10^{-12}}{ln\left\{2^{1/3}\left(\frac{1}{0.02}\right)\left(\frac{\sqrt{26}}{\sqrt{29}}\right)^{2/3}\right\}}$$

$$= \frac{1.1126 \times 10^{-10}}{ln\left\{(1.259921)\,(50)\,(0.9468)^{2/3}\right\}}$$

$$= \frac{1.1126\times10^{-10}}{ln\{(1.259921)\,(50)\,(0.9642)\}}$$

$$= 2.7092\times10^{-11}\ \text{F/m}$$

Capacitance per km is given by,

$$C_{an} = 2.7092\times10^{-11}\times1000$$

$$= 2.7092\times10^{-8}\ \text{F/km}$$

$$\therefore\quad \mathbf{C_{an} = 0.027092\ \mu F/km}$$

Example 2.17 : *If the double circuit 3 phase line has conductors of diameter 2 cm and distance of separation 2 m in hexagonal spacing arrangement. Calculate phase to neutral capacitance for 100 km of line.*

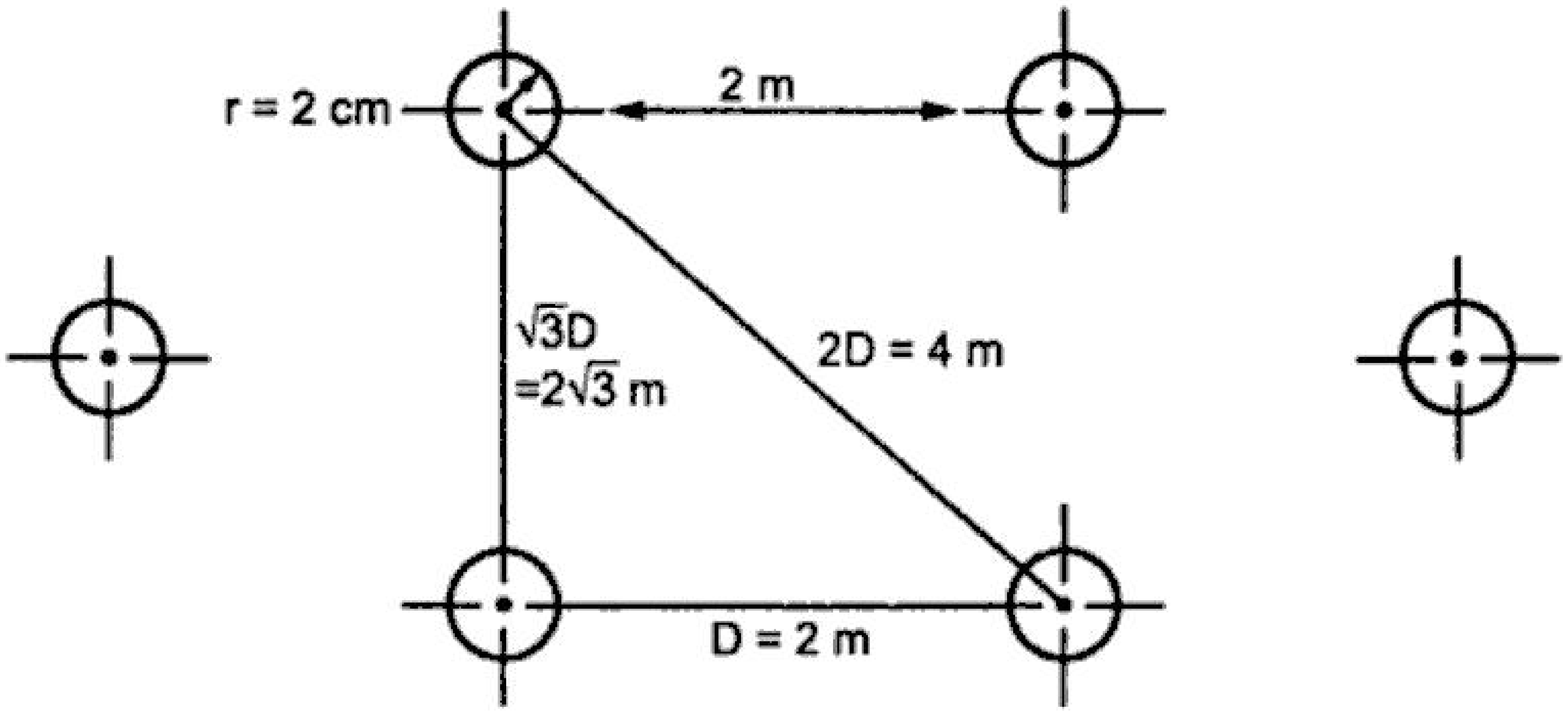

Fig. 2.59

Solution :

$$D = 2\ \text{m},\quad r = 2\ \text{cm} = 2\times10^{-2}\ \text{m}$$

$$\text{Line length} = 100\ \text{km}$$

Capacitance per phase,

$$C_{an} = \frac{2\times2\pi\varepsilon}{ln\left(\frac{\sqrt{3}D}{2\,r}\right)}$$

$$\therefore\quad C_{an} = \frac{4\pi\varepsilon_0}{ln\left(\frac{\sqrt{3}\times2}{2\times2\times10^{-2}}\right)}$$

$$\therefore\quad C_{an} = \frac{4\pi\varepsilon_0}{ln\left(\frac{\sqrt{3}\times10^{2}}{2}\right)}$$

$$\therefore \qquad C_{an} = \frac{4\pi\times 8.854\times 10^{-12}}{ln\left(\frac{173.20}{2}\right)}$$

$$\therefore \qquad C_{an} = 2.4939 \times 10^{-11}\ F/m$$

For a line of length of 100 km,

$$C_{an} = 2.4939 \times 10^{-11} \times 100 \times 10^{3}$$

$$= 2.4939 \times 10^{-6}\ F/Km$$

$$\therefore \qquad \mathbf{C_{an} = 2.4939\ \mu F}$$

Example 2.18 : *Calculate the loop inductance per km of a single phase circuit comprising two parallel conductors 1 m apart and 1 cm in diameter.*

Solution :

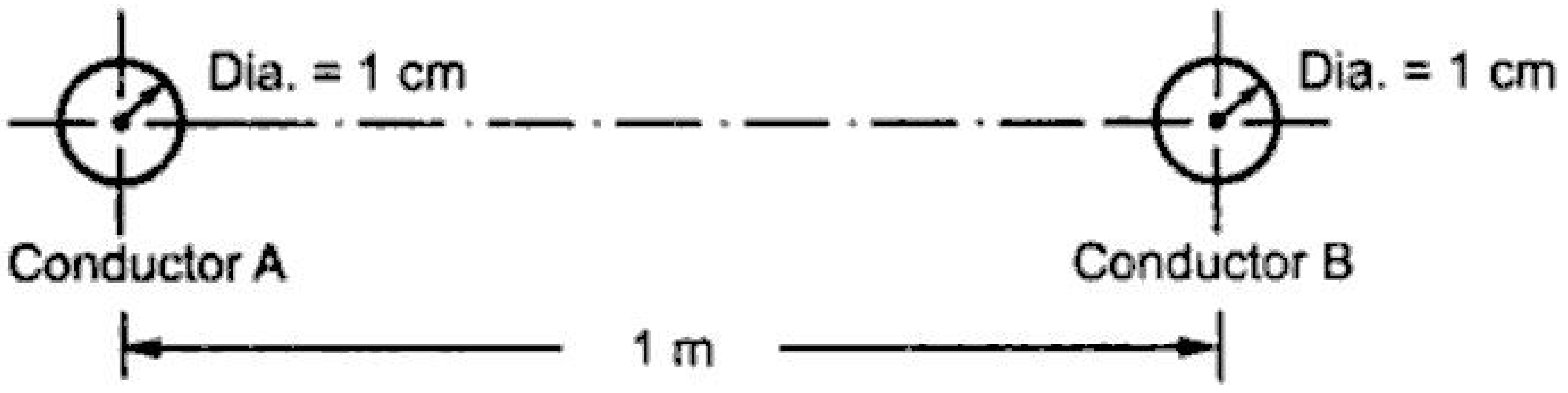

Fig. 2.60

$$r' = \text{GMR of the conductor} = 0.7788\times\frac{\text{Diameter of conductor}}{2}$$

$$= 0.7788\times\frac{1\times 10^{-2}}{2} = 3.894\times 10^{-3}\ m$$

$$D = \text{Distance between the conductors} = 1\ m$$

$$L = 4\times 10^{-7}\ ln\ \frac{D}{r'} = 4\times 10^{-7}\ ln\left(\frac{1}{3.894\times 10^{-3}}\right)$$

$$L = 2.2193\times 10^{-6}\ \ H/m$$

$$L = 2.2193\times 10^{-3}\ \ H/km$$

$\therefore$ Inductance, $\mathbf{L = 22.1932\times 10^{-4}\ H/km}$

Example 2.19 : *Find the inductance per km of a three phase transmission line using 1.24 cm diameter conductors when these are placed at the corners of an equilateral triangle of each side 2 m.*

Solution : Radius of conductor $= \frac{1.8}{2} = 0.9 \text{ cm} = 0.009 \text{ m}$

$$r' = 0.7788\ r = 0.7788 \times 0.009 = 7.0092 \times 10^{-3} \text{ m}$$

$$D_{AB} = 4 \text{ m}, \quad D_{CA} = 6 \text{ m}$$

$$D_{BC} = 9 \text{ m}$$

Inductance per phase,

$$L_A = 2 \times 10^{-7}\, \ln\left(\frac{D_{eq}}{r'}\right) \text{ H/m}$$

$$= 2 \times 10^{-4}\, \ln\left[\frac{\sqrt[3]{D_{AB}\, D_{BC}\, D_{CA}}}{r'}\right] \text{ H/km}$$

$$= 2 \times 10^{-4}\, \ln\left[\frac{\sqrt[3]{(4)(9)(6)}}{7.0092 \times 10^{-3}}\right] = 2 \times 10^{-4}\, \ln\left[\frac{6}{7.0092 \times 10^{-3}}\right]$$

$$= 1.3504 \times 10^{-3} \text{ H/km}$$

For 50 km long transmission line,

$$L_A = 1.3504 \times 10^{-3} \times 50$$

$$\therefore \quad L_A = \mathbf{0.06752\ H}$$

Example 2.21 : *One circuit of a single phase transmission line is composed of 3 solid wires each 2.54 mm in radius. The return circuit is composed of 2 wires each of 5.08 mm radius. The arrangement of conductors is as shown below in the Fig. 2.63. Find the inductance due to the current in each side of the line and the inductance of the complete line in milliHenry per kilometre length.*

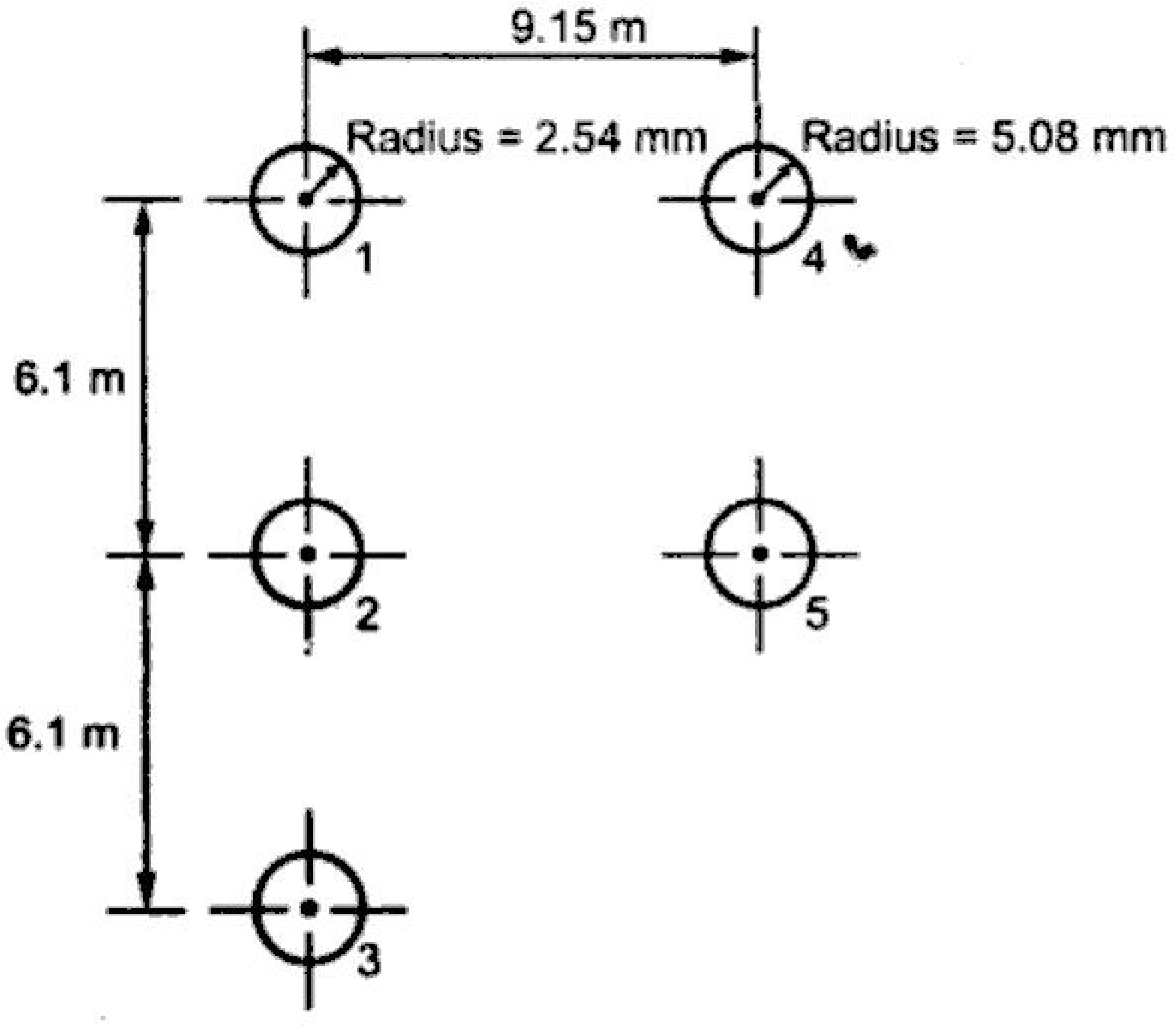

Fig. 2.63

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$$\therefore \qquad C_{AB} = \mathbf{4.3481 \ nF/km}$$

For a line length of 30 km

$$C_{AB} = 4.3481 \times 30 = 130.443 \text{ nF} = \mathbf{130.443 \times 10^{-9} \ F}$$

The charging current is given by,

$$I_C = \frac{V_{ph}}{X_C} = \frac{50000}{\left[\dfrac{1}{2\pi \times 50 \times 130.443 \times 10^{-9}}\right]}$$

$$= 50000 \times 2\pi \times 50 \times 130.443 \times 10^{-9}$$

$$\therefore \qquad I_C = \mathbf{2.0489 \ A}$$

Example 2.27 : *Find the capacitance of a single phase line 40 km long consisting of 2 parallel wires each 5 mm diameter and 1.5 m apart. Determine the capacitance of the line taking into account the effect of ground. The height of the conductors above the ground is 7 m.*

Solution :

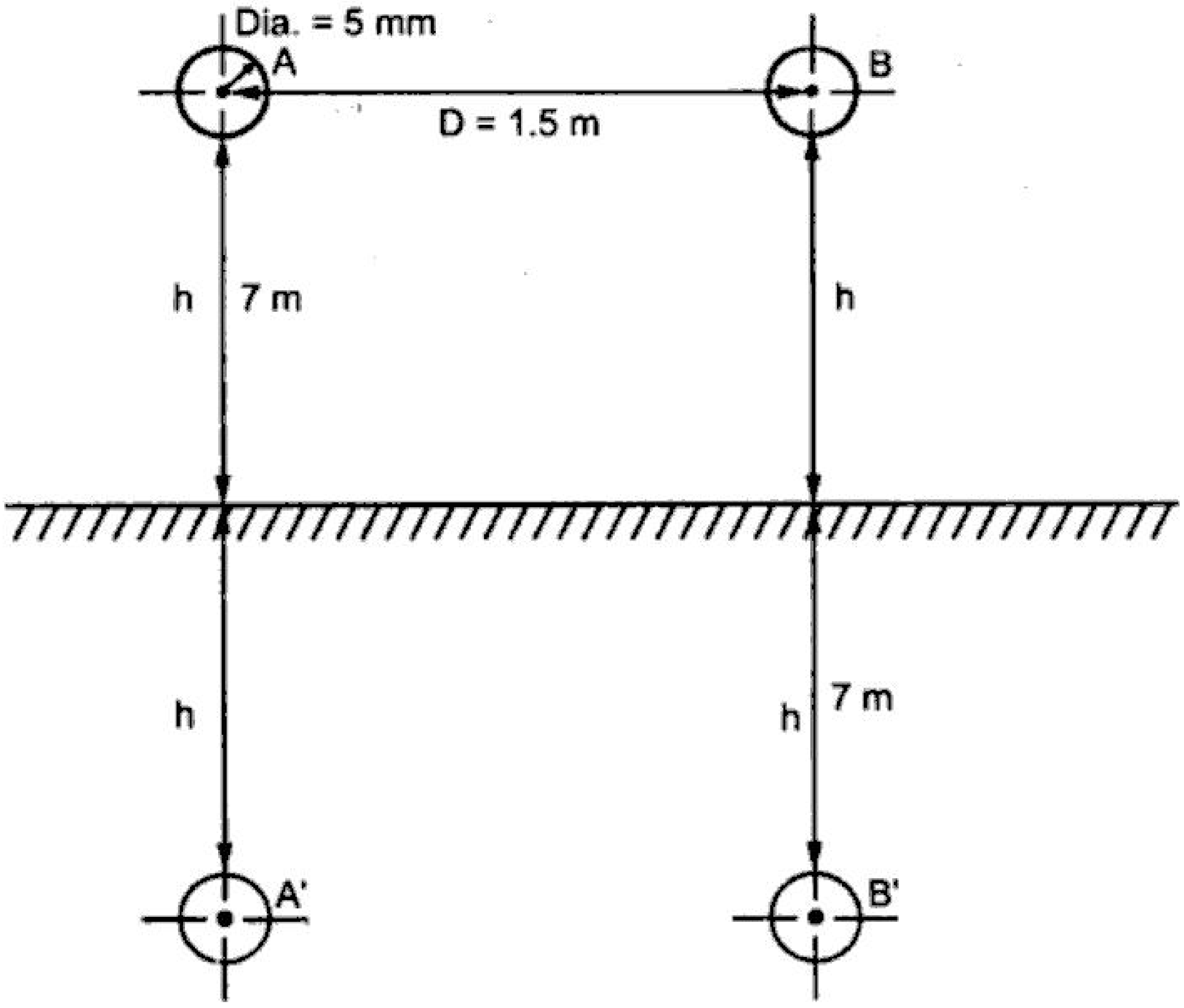

Fig. 2.69

Considering the presence of ground

Here, $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m

$$h = 7 \text{ m}$$

$$D = 1.5 \text{ m}$$

$$r = \frac{d}{2} = \frac{5\times10^{-3}}{2} = 2.5\times10^{-3} \text{ m}$$

We have, $$C_{AB} = \frac{\pi\varepsilon_0}{ln\left[\dfrac{D}{r\sqrt{1+(D^2/4h^2)}}\right]} \text{ F/m} = \frac{\pi\times8.854\times10^{-12}}{ln\left[\dfrac{1.5}{2.5\times10^{-3}\sqrt{1+\dfrac{(1.5)^2}{4(7)^2}}}\right]}$$

$\therefore$ $$C_{AB} = 4.3521\times10^{-12} \text{ F/m}$$

$\therefore$ $$C_{AB} = 4.3521\times10^{-9} \text{ F/km}$$

For a line of length 40 km.

Capacitance, $$C_{AB} = 4.3521\times10^{-9}\times40 = 1.7408\times10^{-7} \text{ F}$$

$$= 0.17408\times10^{-6} \text{ F}$$

$\therefore$ $$C_{AB} = \mathbf{0.1740\ \mu F}$$

Example 2.28 : *A three phase transmission line has symmetrically spaced conductors having diameter of 2 cm each. The spacing between conductors is 1 m. The line is overhead line. Compute capacitance per phase per kilometer.*

Solution :

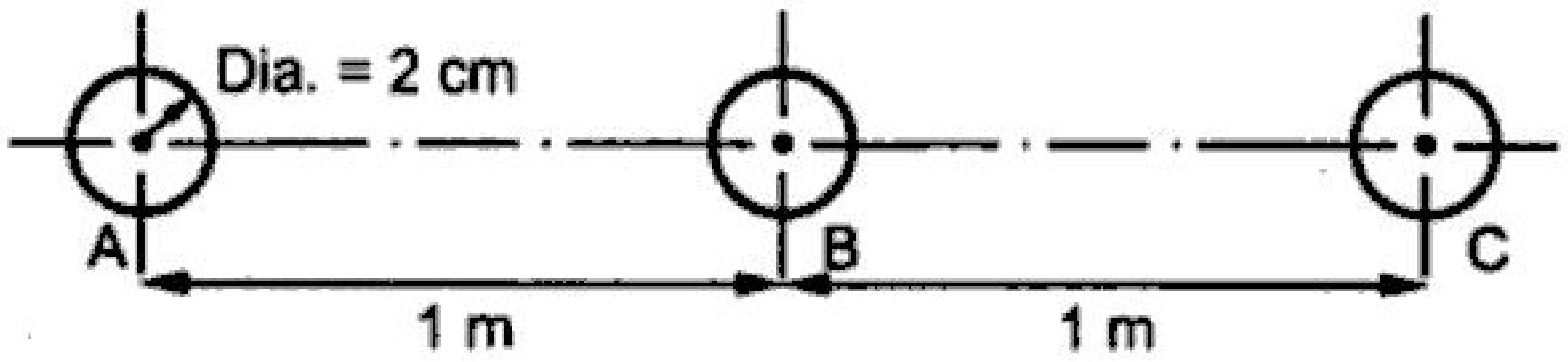

Fig. 2.70

Equivalent equilateral spacing is given by,

$$d = \sqrt[3]{d_{12}\, d_{23}\, d_{31}} = \sqrt[3]{(1)(1)(2)} = \sqrt[3]{2} = 1.2599 \text{ m}$$

$$r = \frac{2\times10^{-2}}{2} = 1\times10^{-2} \text{ m} = 0.01 \text{ m}$$

Line to neutral capacitance is given by,

$$C_{an} = \frac{2\pi\varepsilon_0}{ln\left(\dfrac{d}{r}\right)} \text{ F/m} = \frac{2\pi\times8.854\times10^{-12}}{ln\left(\dfrac{1.2599}{0.01}\right)}$$

$$= \frac{55631\times10^{-11}}{4.8362} = 1.1503\times10^{-11} \ \text{F/m} = 1.1503\times10^{-8} \ \text{F/km}$$

$$= 11.503 \ \text{nF/km}$$

Capacitance per phase per kilometer, C_{an} = **11.503 nF/km.**

➠ **Example 2.29 :** *A 3 phase double circuit line is as shown in the Fig. 2.71. The diameter of each conductor is 2 cm. The line is transposed and carries balanced load. Determine the capacitance per phase to neutral of the line.*

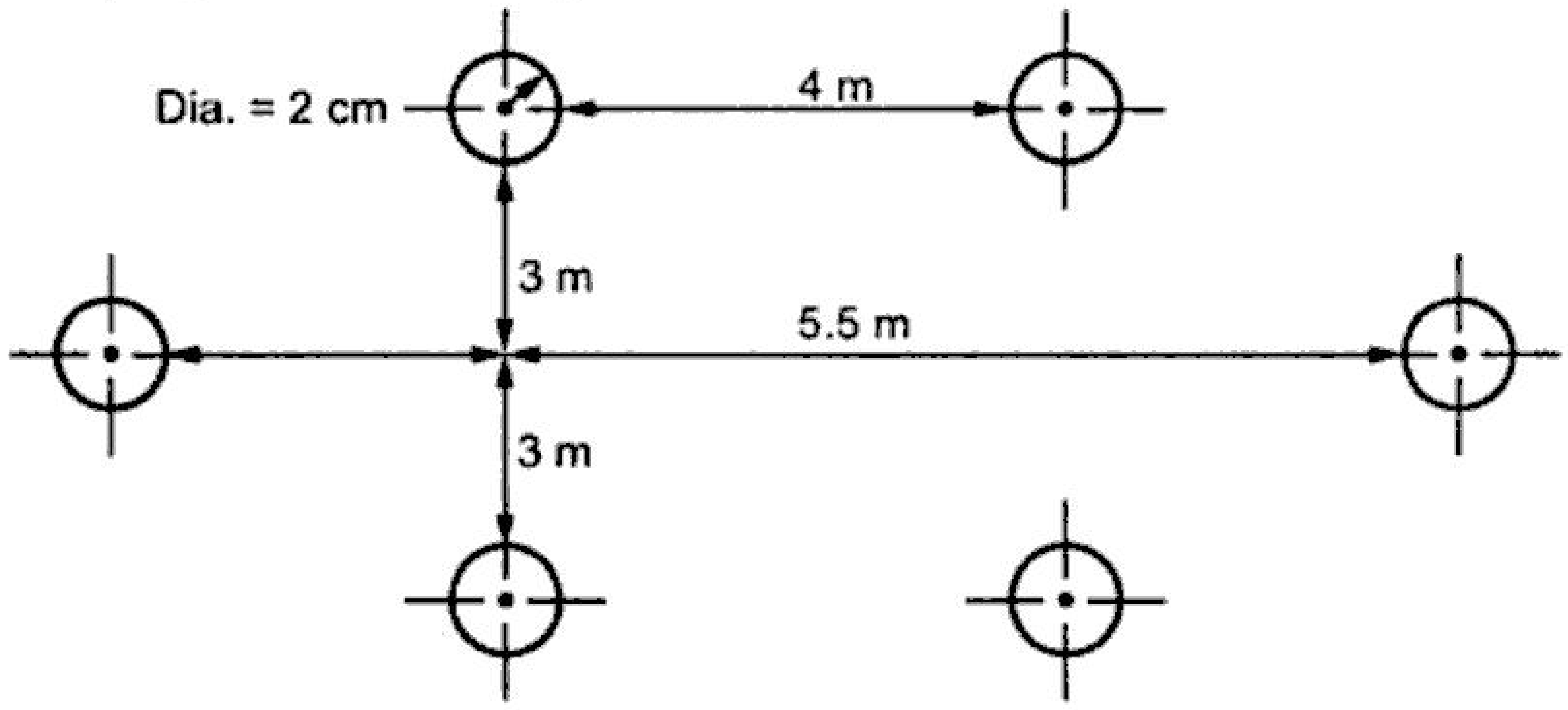

Fig. 2.71

Solution : Consider the arrangement of conductors shown in Fig. 2.71. It consists of three phase double circuit. The radius of each conductor is r.

The voltage between phases a and b can be calculated in order to calculate capacitance.

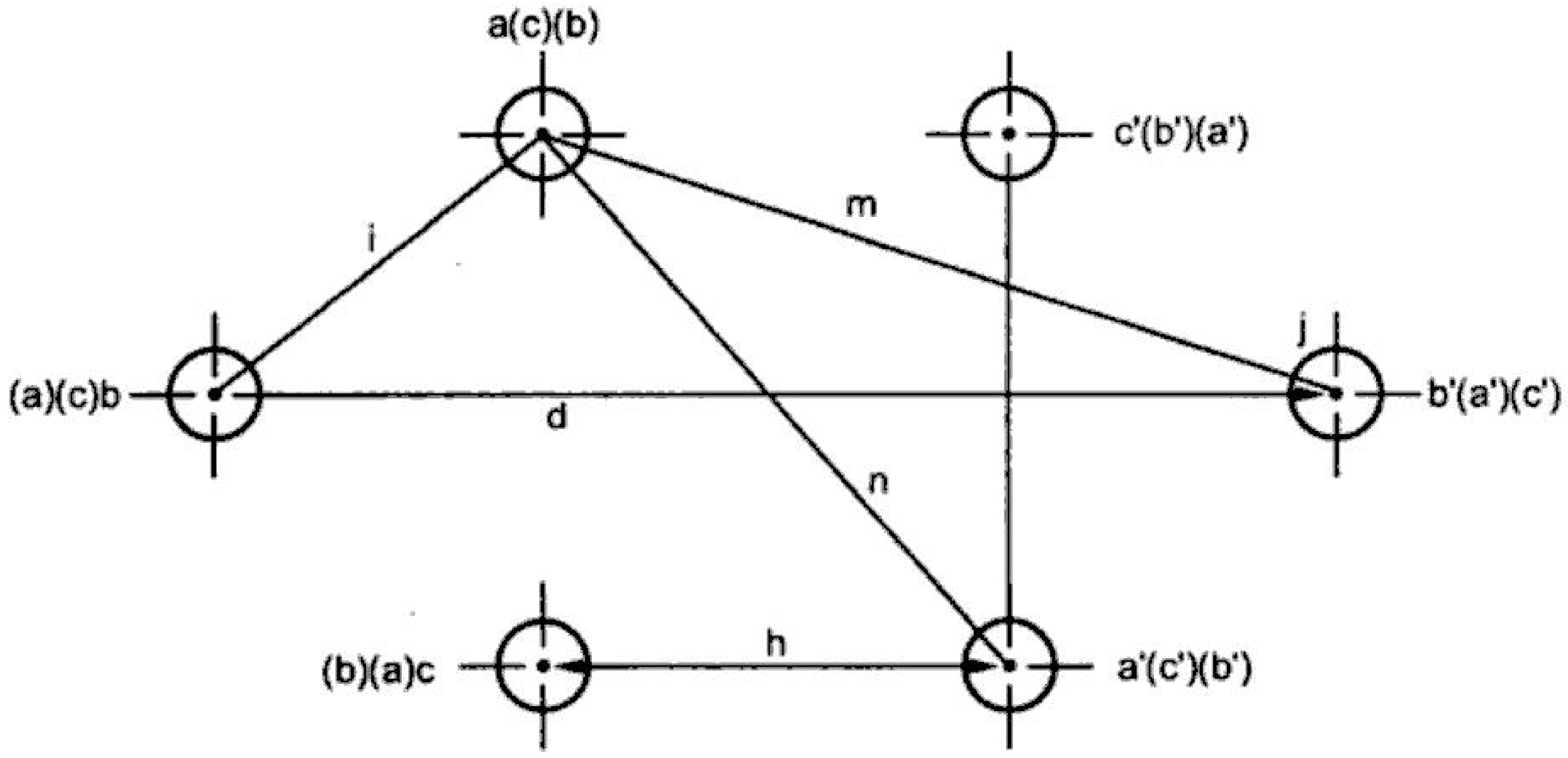

Fig. 2.71 (a)

We have,

$$V_{ab1} = \frac{1}{2\pi\varepsilon}\left\{q_a\left(ln\frac{i}{r}+ln\frac{m}{n}\right)+q_b\left(ln\frac{r}{i}+ln\frac{d}{m}\right)+q_c\left(ln\frac{i}{j}+ln\frac{m}{h}\right)\right\}$$

$$V_{ab2} = \frac{1}{2\pi\varepsilon}\left\{q_a\left(ln\frac{i}{r}+ln\frac{m}{d}\right)+q_b\left(ln\frac{r}{i}+ln\frac{n}{m}\right)+q_c\left(ln\frac{j}{i}+ln\frac{h}{m}\right)\right\}$$

$$V_{ab3} = \frac{1}{2\pi\varepsilon}\left\{q_a\left(ln\frac{j}{r}+ln\frac{h}{n}\right)+q_b\left(ln\frac{r}{j}+ln\frac{n}{h}\right)+q_c\left(ln\frac{i}{i}+ln\frac{m}{m}\right)\right\}$$

$$V_{ab} = \frac{1}{3}\left[V_{ab1}+V_{ab2}+V_{ab3}\right]$$

$$= \frac{1}{3}\left[\frac{1}{2\pi\varepsilon}\left\{q_a\left(ln\frac{i^2m^2jh}{r^3n^2d}\right)+q_b\left(ln\frac{r^3n^2d}{i^2m^2jh}\right)+q_c\,ln\left(\frac{i^2m^2jh}{i^2m^2jh}\right)\right\}\right]$$

$$= \frac{1}{6\pi\varepsilon}\left[q_a\,ln\frac{i^2m^2jh}{r^3n^2d}+q_b\,ln\frac{r^3n^2d}{i^2m^2jh}\right]$$

Similarly,

$$V_{ac} = \frac{1}{6\pi\varepsilon}\left[q_a\,ln\frac{i^2m^2jh}{r^3n^2d}+q_c\,ln\frac{r^3n^2d}{i^2m^2jh}\right]$$

We have,

$$V_{ab}+V_{ac} = 3\,V_{an}$$

$$3V_{an} = \frac{1}{6\pi\varepsilon}\left\{2q_a\,ln\frac{i^2m^2jh}{r^3n^2d}+(q_b+q_c)\,ln\frac{r^3n^2d}{i^2m^2jh}\right\}$$

Also, $q_a+q_b+q_c=0 \qquad q_b+q_c=-q_a$

$$3V_{an} = \frac{1}{6\pi\varepsilon}\left\{[2q_a-(-q_a)]\,ln\frac{i^2m^2jh}{r^3n^2d}\right\}$$

$$3V_{an} = \frac{1}{6\pi\varepsilon}(3q_a)\,ln\frac{i^2m^2jh}{r^3n^2d}$$

$$\therefore \qquad V_{an} = \frac{1}{6\pi\varepsilon}\,q_a\,ln\frac{i^2m^2jh}{r^3n^2d}$$

Now,

$$C_{an} = \frac{q_a}{V_{an}} = \frac{6\pi\varepsilon}{ln\frac{i^2m^2jh}{r^3n^2d}} = \frac{(2\pi\varepsilon)(3)}{ln\frac{i^2m^2jh}{r^3n^2d}} = \frac{2\pi\varepsilon}{\frac{1}{3}ln\left(\frac{i^2m^2jh}{r^3n^2d}\right)}$$

$$\therefore \qquad C_{an} = \frac{2\pi\varepsilon}{ln\left(\frac{i^2m^2jh}{r^3n^2d}\right)^{1/3}}$$

$$\text{Total capacitance per phase} = 2\,C_{an} = \frac{4\pi\varepsilon}{ln\left(\dfrac{i^2\,m^2 j\,h}{r^3\,n^2 d}\right)}$$

Now let us find the various distances from given problem

h = 4 m ; j = 6 m, dia = 2 cm, Radius r = 1 cm, d = 5.5 m

$$i = \left[\left(\frac{j}{2}\right)^2 + \left(\frac{d-h}{2}\right)^2\right]^{1/2} = (3)^2 + (0.75)^2 = 3.0923\ \text{m}$$

$$n = \left(j^2 + h^2\right)^{1/2} = \left(6^2 + 4^2\right)^{1/2} = 7.2111\ \text{m}$$

$$m = \left[3^2 + (4.75)^2\right]^{1/2} = 5.6180\ \text{mt}$$

$$\text{Total capacitance per phase} = \frac{4\pi\varepsilon_0}{ln\left(\dfrac{i^2\,m^2\,j\,h}{r^3 n^2 d}\right)} = \frac{4\times\pi\times 8.854\times 10^{-12}}{ln\left[\dfrac{(3.0923)^2 (5.6180)^2\,(6)(4)}{\left(1\times 10^{-2}\right)^3 (7.2111)^2 (5.5)}\right]}$$

$$= \frac{1.1126\times 10^{-10}}{ln\left[\dfrac{7243.32}{2.8599\times 10^{-4}}\right]} = \frac{1.1126\times 10^{-10}}{17.047}$$

$$= 6.5265\times 10^{-12}\ \text{F/m}$$

$$= \mathbf{0.0065265\ \mu F/km}$$

Example 2.30 : *Determine the inductance of a 3 phase, line operating at 50 Hz and the conductors are arranged as shown in Fig. 2.72. The conductor diameter is 0.7 cm.*

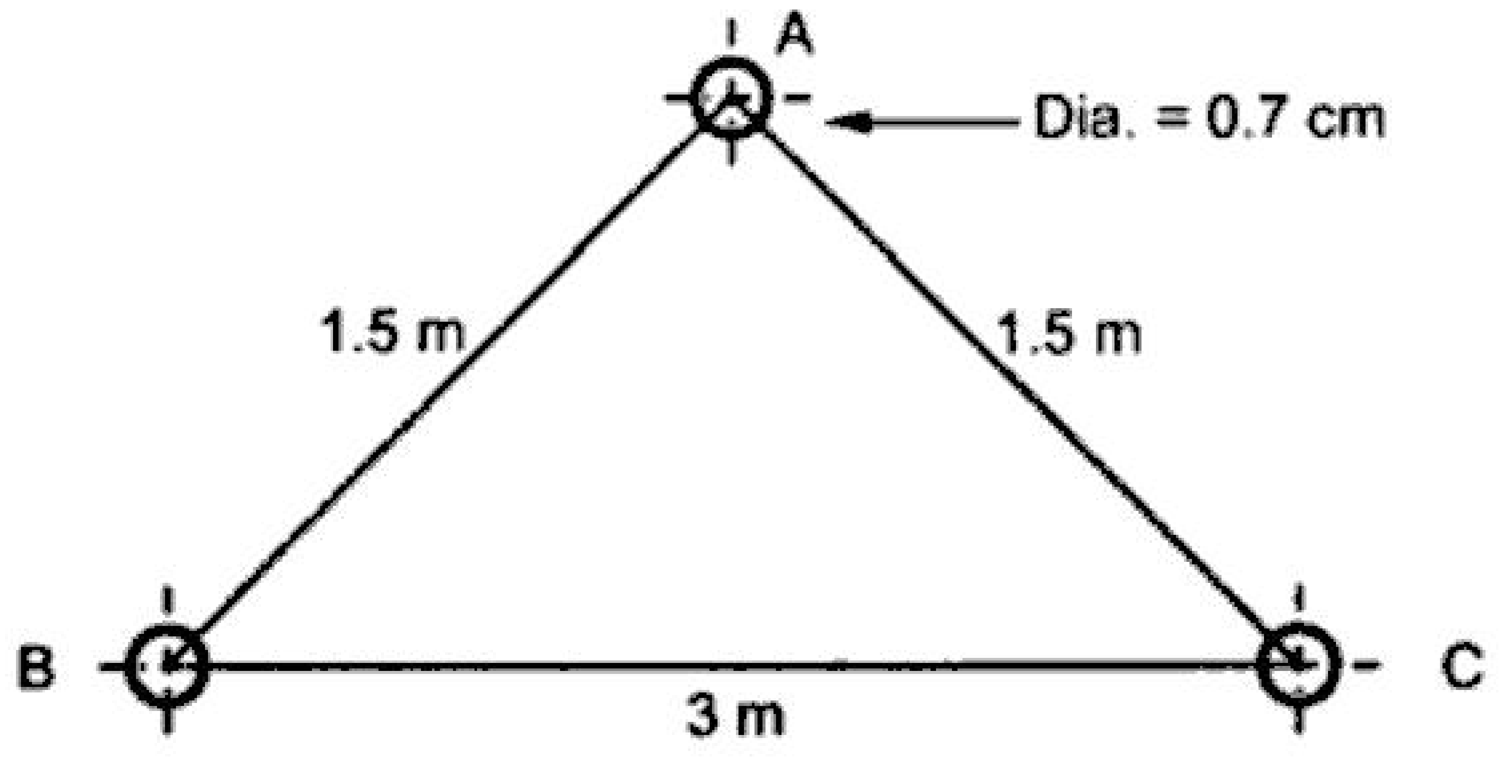

Fig. 2.72

Solution : Radius of conductor $= \frac{0.7}{2} = 0.35$ cm $= 3.5 \times 10^{-3}$m

$$r' = 0.7788 \times 3.5 \times 10^{-3} = 2.7258 \times 10^{-3} \text{m}$$

$$D_{AB} = 1.5 \text{ m}$$

$$D_{BC} = 3 \text{ m}$$

$$D_{CA} = 1.5 \text{ m}$$

$$D_{eq} = \sqrt[3]{D_{AB} \cdot D_{BC} \cdot D_{CA}} = \sqrt[3]{(1.5)(3)(1.5)} = 1.8898 \text{ m}$$

Inductance per phase,

$$L_A = 2 \times 10^{-7} \, ln \left[\frac{D_{eq}}{r'}\right] \text{H/m}$$

$$= 2 \times 10^{-7} \, ln \left[\frac{1.8898}{2.7258 \times 10^{-3}}\right]$$

$$= 1.3083 \times 10^{-6} \text{ H/m}$$

$$= 1.3083 \times 10^{-3} \text{ H/km}$$

$$\therefore \quad L_A = \mathbf{1.31 \text{ mH/km}}$$

Example 2.31 : *Determine the inductance of the double circuit line shown in Fig. 2.73. The self GMD of the conductor is 0.007 metre.*

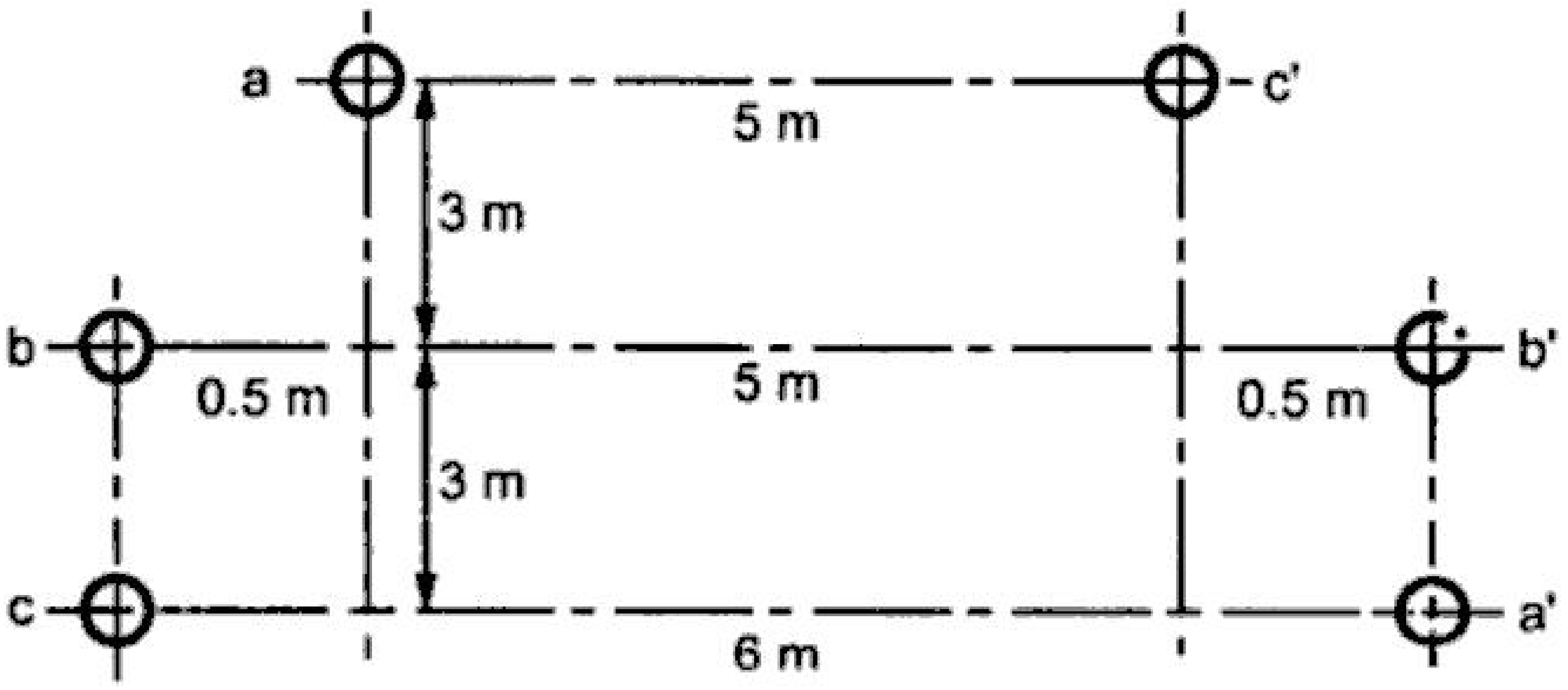

Fig. 2.73

Solution : Self GMD of the conductor = 0.007 m

$D_{ab} = \sqrt{(3)^2 + (0.5)^2} = 3.041$ m ; $D_{ba'} = \sqrt{(3)^2 + (6)^2} = 6.7082$ m

$D_{ab'} = \sqrt{(3)^2 + (5.5)^2} = 6.26$ m $= D_{bc'}$; $D_{ca} = \sqrt{(6)^2 + (0.5)^2} = D_{b'c} = 6.020$ m

$$D_{aa'} = \sqrt{(6)^2 + (5.5)^2} = 8.13 \text{ m} = D_{cc'}$$

D_S is equivalent GMD of one phase which is given by,

$$D_S = \sqrt[3]{D_{S1} \cdot D_{S2} \cdot D_{S3}}$$

$$D_{S1} = \sqrt[4]{D_{aa'} . D_{aa} D_{a'a} D_{a'a'}} = \sqrt[4]{(8.13)\,(0.007)\,(8.13)\,(0.007)}$$

$$= 0.2385 \text{ m}$$

$$D_{S2} = \sqrt[4]{D_{bb'} . D_{bb} D_{b'b} D_{b'b'}} = \sqrt[4]{(6)\,(0.007)\,(6)\,(0.007)} = 0.2049 \text{ m}$$

$$D_{S3} = \sqrt[4]{D_{cc'} . D_{cc} D_{c'c} D_{c'c'}} = \sqrt[4]{(8.13)\,(0.007)\,(8.13)\,(0.007)} = 0.2385 \text{ m}$$

$$D_S = \sqrt[3]{(0.2385)\,(0.2049)\,(0.2385)} = 0.2267 \text{ m}$$

$$D_m = \sqrt[3]{D_{AB} D_{BC} D_{CA}}$$

$$D_{AB} = \sqrt[4]{D_{ab} D_{ab'} . D_{ba} D_{ba'}} = \sqrt[4]{(3.041)\,(6.26)\,(3.041)\,(6.7082)}$$

$$= 4.4391 \text{ m}$$

$$D_{BC} = \sqrt[4]{D_{bc} D_{bc'} . D_{cb} D_{cb'}} = \sqrt[4]{(3)\,(6.26)\,(3)\,(6.7082)} = 4.4091 \text{ m}$$

$$D_{CA} = \sqrt[4]{D_{ca} D_{ca'} . D_{ac} D_{ac'}} = \sqrt[4]{(6.020)(6)(6.020)(5)} = 5.7422 \text{ m}$$

$$D_m = \sqrt[3]{(4.4391)\,(4.4091)\,(5.7422)} = 4.8258 \text{ m}$$

$$\text{Inductance per phase per km} = 2 \times 10^{-4}\, ln \frac{D_m}{D_s}$$

$$= 2 \times 10^{-4}\, ln \left[\frac{4.8258}{0.2267}\right]$$

$$= 6.1162 \times 10^{-4} \text{ H}$$

$\therefore$ Inductance per phase per km = **0.6116 mH**

Example 2.32 : *Determine the inductance of the double cicuit line shown in Fig. 2.74 below. The self GMD of the conductors is 0.0069 metre.*

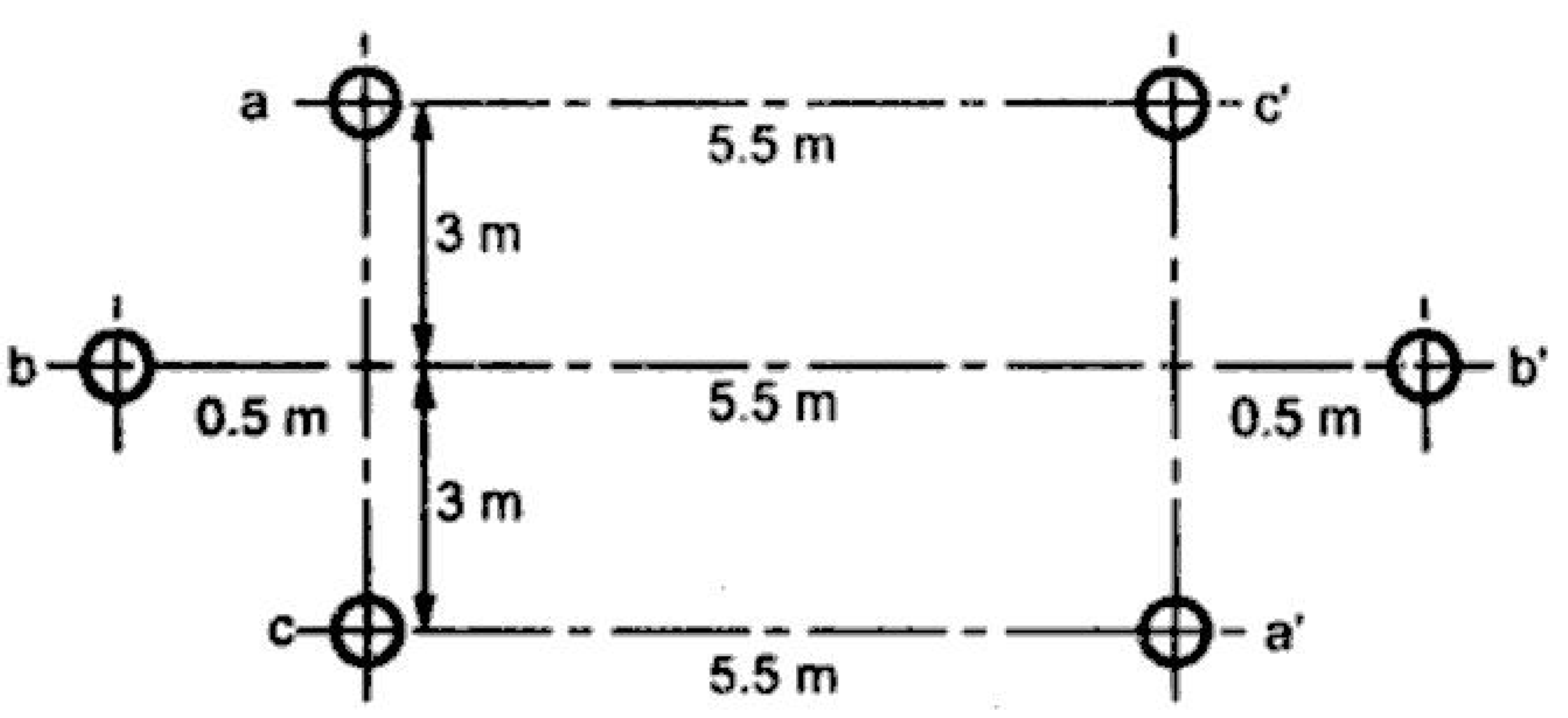

Fig. 2.74

The oil pressure compresses the paper insulation, eliminating the possibility of formation of voids. When cable is heated, the oil expands but expanded oil is collected in the tank. While when cable is cooled, extra oil is supplied by the tank to maintain the oil pressure. In this type of cable the oil channel is within the conductor, hence it is called **single core conductor channel oil filled cables**. The other construction of the cable is similar to that of solid type cables.

Another type of single core oil filled cable is the **sheath channel oil filled cable**. In this type, the conductor is solid with a paper insulation. While the oil ducts are provided between the dielectric and the lead sheath.

The construction of sheath channel oil filled cable is shown in the Fig. 3.7. The laying of such cables must be done very carefully.

The three core oil filled cables use the shielded type construction. The oil channels are located in the spaces which are normally occupied by the filler material. The three oil channels are of perforated metal ribbon tubing. All the channels are at earth potential. The construction is shown in the Fig. 3.8. As the pressure tanks are required all along the route of these cables, the lengths of these cables are limited. Leakage of oil is another serious problem associated with these cables. Automatic signalling units are located to indicate the fall in oil pressure in any of the phases.

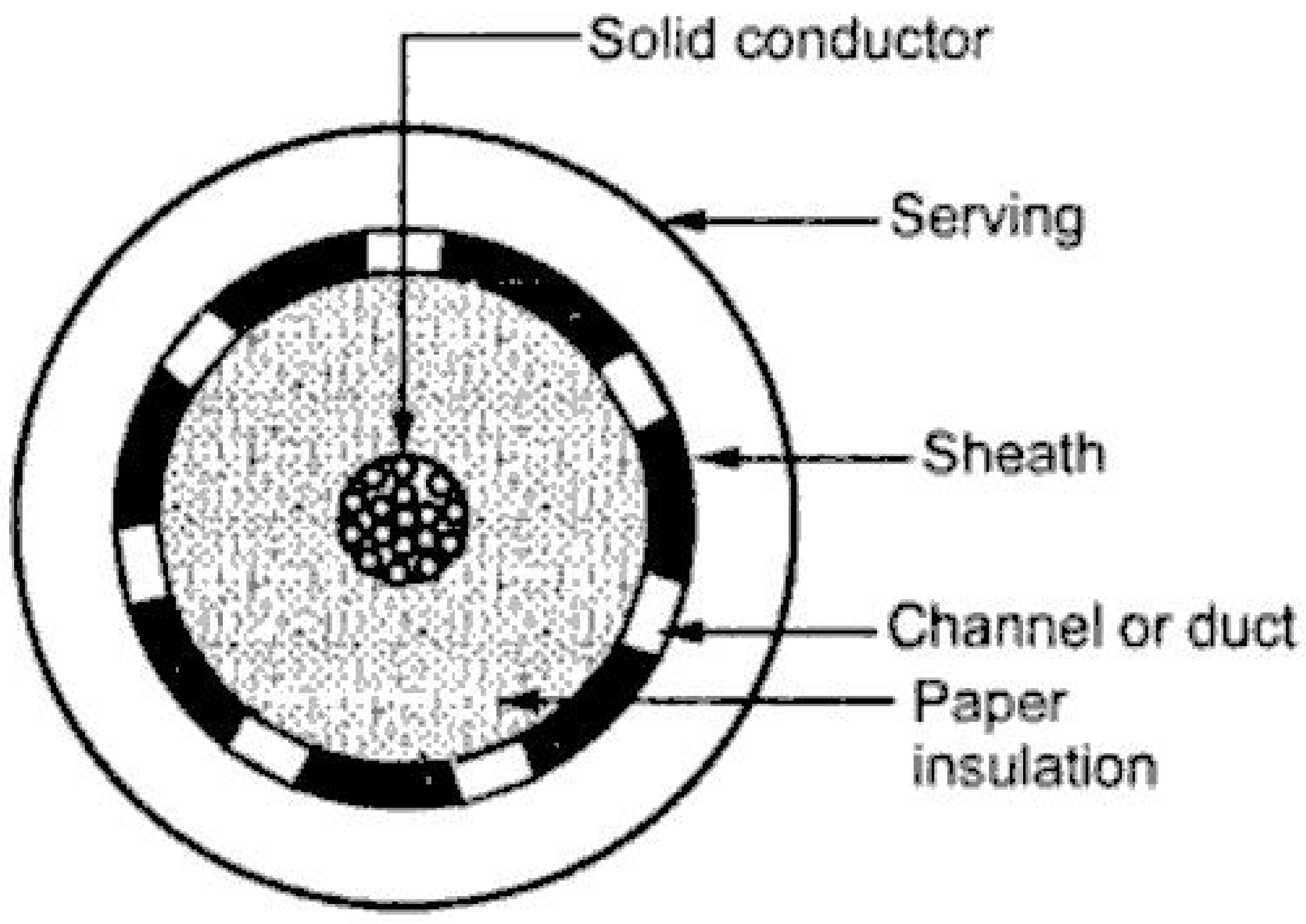

Fig. 3.7 Sheath channel single core oil filled cable

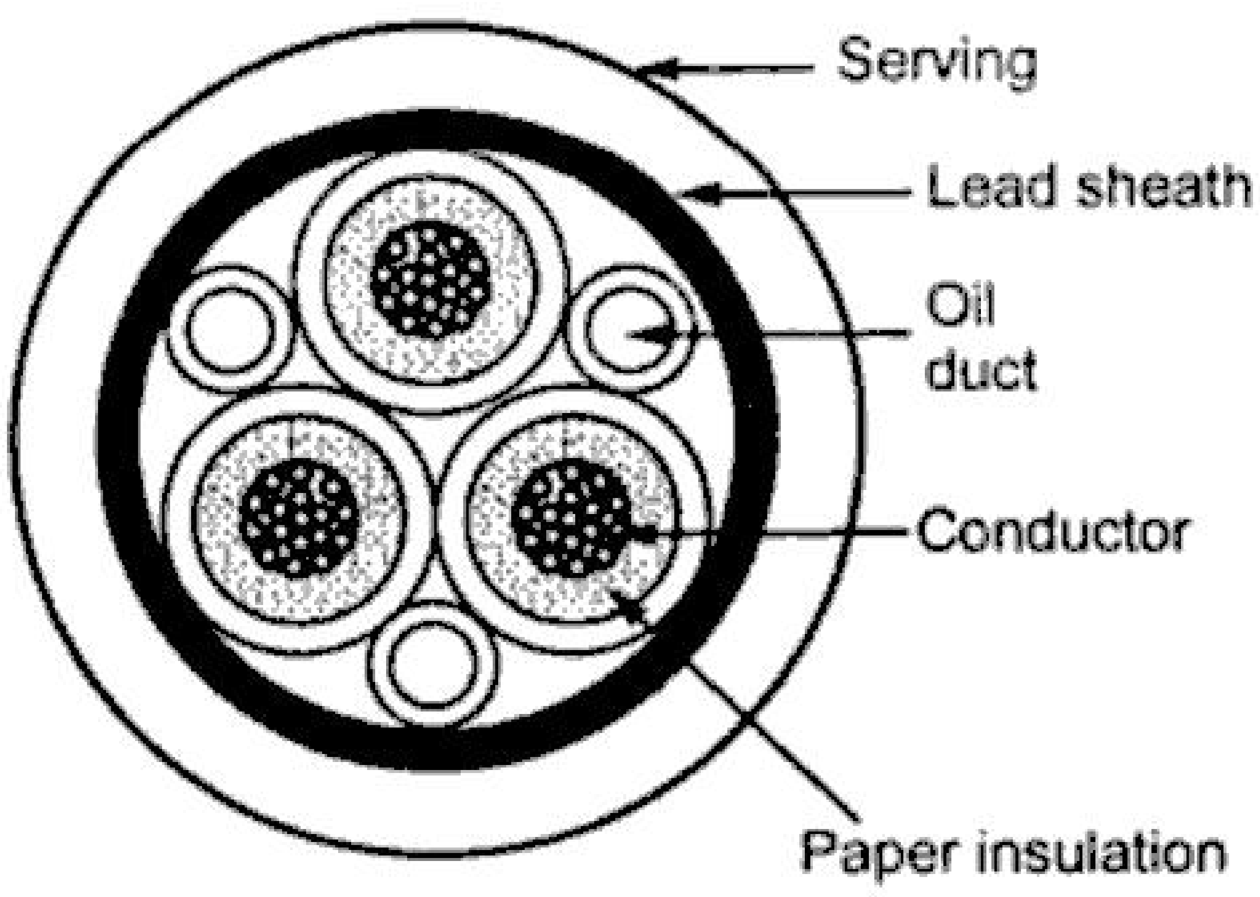

Fig. 3.8 Oil filled three core cable

3.4.4.1 Advantages

The various advantages of oil filled cables are,

1. The thickness of insulation required is less hence smaller in size and weight.
2. The thermal resistance is less hence current carrying capacity is more.
3. The possibility of voids is completely eliminated.
4. The allowable temperature range is more than solid type cables.

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1. Poly Vinyl Chloride (PVC)
2. Paper
3. Cross Linked Polythene
4. Vulcanized India Rubber (VIR)

3.5.1 Poly Vinyl Chloride (PVC)

It is thermo plastic synthetic compound. It is available in the powder form and is obtained from polymerisation of acetylene. This powder is chemically inert, non-inflammable, odourless, tasteless and insoluble. It is combined with plastic compound and a gel is used over the conductor to obtain the insulation.

It has following characteristics,

1. Good dielectric strength of 17 kV/mm
2. Chemically inert.
3. Non-hygroscopic.
4. Resistant to corrosion.
5. Maximum continuous temperature rating of 75℃.
6. High electrical resistivity.

The mechanical properties like elasticity of PVC are not as good as rubber so PVC cables are used for low and medium voltage domestic, industrial lights and power installations.

3.5.2 Paper

The paper is very cheap insulating material. Its dielectric strength is also high but it is hygroscopic in nature. When it is dry its insulation resistance is very high but a small amount of moisture reduces its insulation resistance to a very low value. Thus it is impregnated in an insulating oil. After impregnating also it has a tendency to absorb the moisture. Hence paper cables are never left unsealed and provided with the protective covering. When not in use, paper cable ends are temporarily covered with wax or tar.

The paper has following characteristics,

1. High dielectric strength of 20 kV/mm.
2. Higher thermal conductivity.
3. Low capacitance
4. High durability
5. Low cost
6. Maximum continuous temperature rating of 80 ℃
7. High insulation resistance when dry.

It is used in high voltage power cable manufacturing. The paper cables are preferred when the cable route has very few joints and hence generally used for low voltage distribution in thickly populated areas.

3.5.3 Cross Linked Polythelene

The cables using cross linked polythelene as the insulating material are called XLPE cables.

The low density polythelene is treated specially due to which there occurs cross linking of carbon atoms in it. This results into a new material which has following properties,

1. High dielectric strength of 20 to 40 kV/mm
2. Non-inflammable : If at all the continuous flame is applied its burning stops after very few centimetres away from the flame.
3. Extremely high melting point.
4. Light in weight and flexible.
5. Mechanically strong.
6. High temperature withstanding capability.
7. Low moisture absorption.
8. Maximum continuous temperature rating of 90 °C.

XLPE cables are directly laid on soil bed and are used for the voltages upto and including 33 kV.

3.5.4 Vulcanized India Rubber (VIR)

This is the most olden insulating material developed during 1880-1930. The pure rubber is very soft and it cannot withstand high temperatures hence it is 20 to 40 % of India rubber mixed with mineral matter such as zinc oxide, red lead etc. with a little bit of sulphur in it.

It has following characteristics,

1. Good dielectric strength of 15 kV/mm.
2. Good mechanical strength.
3. Durable and wear resistant.
4. Good insulation resistance.
5. Remain more elastic than pure rubber.

But it has number of drawbacks such as,

1. It absorbs moisture, slightly.
2. It has low melting point.
3. The sulphur content attack the copper conductor and changes the VIR insulation colour. Hence copper conductors to be used with VIR insulation must be tinned.
4. Short span of life.

The use of VIR is very limited nowadays and is used for low and moderate voltage cables i.e. distribution systems only.

3.7.2 Economical Core Diameter

In practice, the maximum stress value should be as low as possible. When the voltage V and sheath diameter D are fixed, the only parameter to be selected is the core diameter d. So d should be selected for which g_{max} value is minimum.

The value of g_{max} will be minimum when $\frac{\partial g_{max}}{\partial d} = 0$

Now
$$g_{max} = \frac{2V}{d\,ln\left[\frac{D}{d}\right]}$$

$$\frac{\partial g_{max}}{\partial d} = \frac{d\,ln\left[\frac{D}{d}\right]\frac{\partial}{\partial d}(2V) - 2V\frac{\partial}{\partial d}\left[d\,ln\left(\frac{D}{d}\right)\right]}{\left[d\,ln\left(\frac{D}{d}\right)\right]^2}$$

$$= \frac{0 - 2V\frac{\partial}{\partial d}\left[d\,ln\left(\frac{D}{d}\right)\right]}{\left[d\,ln\left(\frac{D}{d}\right)\right]^2} \quad \text{as} \quad \frac{\partial(2V)}{\partial d} = 0$$

$$= \frac{-2V}{\left[d\,ln\left(\frac{D}{d}\right)\right]^2}\left\{ln\left(\frac{D}{d}\right) + d\cdot\frac{1}{\left(\frac{D}{d}\right)}\cdot\left(\frac{-D}{d^2}\right)\right\}$$

As
$$\frac{\partial}{\partial x}\left[ln\left(\frac{c}{x}\right)\right] = \frac{1}{\left(\frac{c}{x}\right)}\cdot\frac{\partial}{\partial x}\left[\frac{c}{x}\right] = \frac{1}{\left(\frac{c}{x}\right)}\left(\frac{-c}{x^2}\right)$$

$$\therefore \quad \frac{\partial g_{max}}{\partial d} = \frac{-2V}{\left[d\,ln\left(\frac{D}{d}\right)\right]^2}\left\{ln\left(\frac{D}{d}\right) - 1\right\} \qquad \dots (3)$$

Now the value of $\frac{\partial g_{max}}{\partial d}$ must be zero to get minimum g_{max}.

$$\therefore \quad ln\left(\frac{D}{d}\right) - 1 = 0$$

$$\therefore \quad ln\left(\frac{D}{d}\right) = 1$$

$$\therefore \quad \frac{D}{d} = e^1 = 2.718$$

$$\therefore \quad \boxed{d = \frac{D}{2.718}} \qquad \dots (4)$$

Key Point : ***The core diameter must be 1/2.718 times the sheath diameter D so as to give the minimum value of g_{max}.***

The value of minimum g_{max} is,

$$\text{Minimum } g_{max} = \frac{2V}{d} \qquad \ldots \text{As } ln\left(\frac{D}{\frac{D}{2.718}}\right) = 1 \qquad \ldots (5)$$

$$\therefore \quad \text{Minimum } g_{max} = \frac{V}{r} \qquad \ldots \text{As } r = \frac{d}{2}$$

For high voltage cables, for a required g_{max} if d is determined by the expression (5), it gives very large values of d than required for current carrying capacity. And such extra copper required can increase the cost tremendously. Hence to increase d without the use of an extra copper following methods are used :

1. Aluminium is used instead of copper as the aluminium size is more than copper for the same current carrying capacity.
2. Using stranded copper conductors around a dummy core of jute or hemp.
3. Using stranded copper conductors around a lead tube instead of hemp.

Example 3.2 : *A concentric cable has a conductor diameter of 0.6 cm and the insulation thickness of 1.4 cm. If the dielectric used has relative permittivity of 5, calculate the capacitance for 1 km length of the cable.*

Solution : $d = 0.6 \text{ cm}$ and $t = 1.4 \text{ cm}$

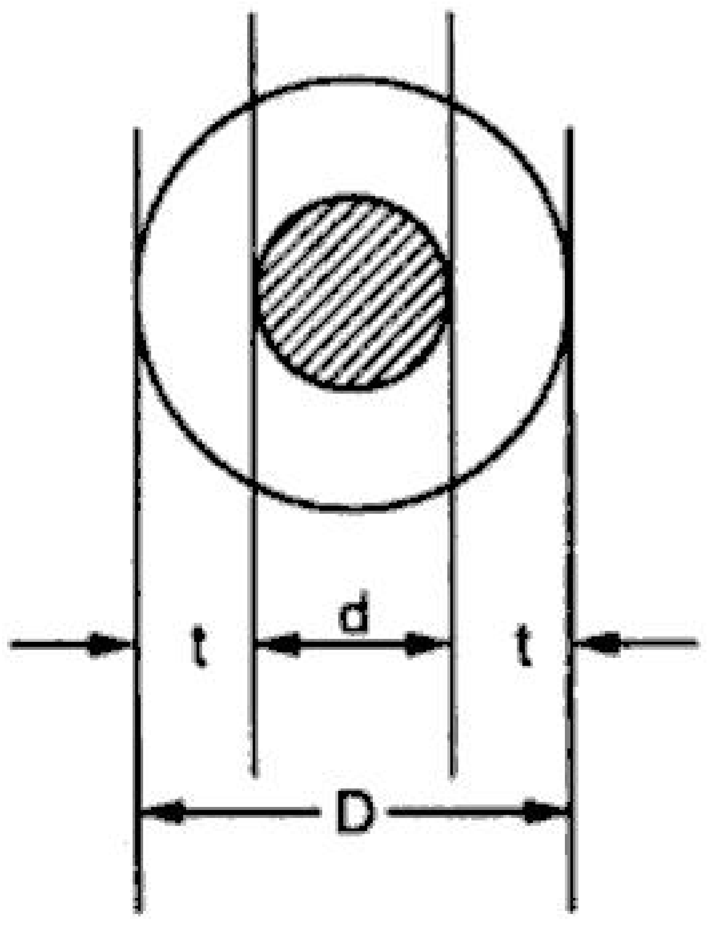

Fig. 3.15

$$\therefore \quad D = d + 2t$$

$$= 0.6 + (2 \times 1.4) = 3.4 \text{ cm}$$

$$\therefore \quad C = \frac{2\pi\varepsilon_0\varepsilon_r}{ln\left[\frac{D}{d}\right]} \text{ F/m}$$

Now $\varepsilon_r = 5$ and $l = 1 \text{ km} = 1000 \text{ m}$

$$\therefore \quad C = \frac{2\pi \times 8.854 \times 10^{-12} \times 5}{ln\left[\frac{3.4 \times 10^{-2}}{0.6 \times 10^{-2}}\right]} \times 1000 \text{ F} = \mathbf{0.1603\ \mu F}$$

Example 3.3 : *A single core cable is used on a 66 kV, 3 phase system. The core diameter is 1 cm while the insulation thickness is 1.5 cm. If PVC of relative permittivity 4.8 is used as dielectric, calculate the capacitance of cable and its charging current. The supply frequency is 50 Hz. Assume cable length to be 1.5 km.*

Solution : $d = 1$ cm, $t = 1.5$ cm, $\varepsilon_r = 4.8$, $f = 50$ Hz, $l = 1.5$ km

$$\therefore \quad D = d + 2t = 1 + 2 \times 1.5 = 4 \text{ cm}$$

$$\therefore \quad C = \frac{2\pi\varepsilon_0\varepsilon_r}{ln\left[\frac{D}{d}\right]} = \frac{2\pi\times 8.854\times10^{-12}\times4.8}{ln\left[\frac{4\times10^{-2}}{1\times10^{-2}}\right]} \text{ F/m}$$

$$= \mathbf{1.9262\times10^{-10} \text{ F/m}}$$

$$\therefore \quad C = 1.9262\times10^{-10}\times l \text{ F} = 1.9262\times10^{-10}\times1.5\times10^{3}$$

$$= \mathbf{0.2889\ \mu F}$$

Now $$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi\times0.2889\times10^{-6}\times50} = \mathbf{11.016\ k\Omega}$$

$$V_{line} = 66 \text{ kV}$$

$$\therefore \quad V_{ph} = \frac{V_{line}}{\sqrt{3}} = \frac{66\times10^{3}}{\sqrt{3}} = \mathbf{38.1051\ kV}$$

$$\therefore \quad I = \text{Charging current} = \frac{V_{ph}}{X_C} = \frac{38.1051\times10^{3}}{11.016\times10^{3}} = \mathbf{3.459\ A}$$

Example 3.4 : *A concentric cable has a core diameter of 0.8 cm. The sheath diameter is 3.2 cm. If the cable is tested with a voltage of 33 kV, calculate the maximum and minimum stress in the insulation.*

Solution : $d = 0.8$ cm, $D = 3.2$ cm, $V = 33$ kV

$$g_{max} = \frac{2V}{d\,ln\left[\frac{D}{d}\right]} = \frac{2\times33\times10^{3}}{0.8\times10^{-2}\,ln\left[\frac{3.2\times10^{-2}}{0.8\times10^{-2}}\right]}$$

$$= 5.951\times10^{6} \text{ V/m} = \mathbf{5.951\ kV/mm\ (r.m.s.)}$$

and $$g_{min} = \frac{2V}{D\,ln\left[\frac{D}{d}\right]} = \frac{2\times33\times10^{3}}{3.2\times10^{-2}\,ln\left[\frac{3.2\times10^{-2}}{0.8\times10^{-2}}\right]} = 1.4877\times10^{6} \text{ V/m}$$

$$= \mathbf{1.4877\ kV/mm\ (r.m.s.)}$$

Example 3.5 : *Find the most economical diameter of a single core cable to be used on 66 kV, 3 phase system, if the peak permissible stress is not to exceed 50 kV/cm. Also find the overall diameter.*

Solution : $V_{line} = 66$ kV, $g_{max} = 50$ kV/cm (peak)

$$\therefore \quad C_{12} = C_C + \frac{1}{3} C_s + \frac{1}{2} [C_C + \frac{1}{3} C_s]$$

$$= 0.08 + \frac{0.2}{3} + \frac{1}{2}\left[0.08 + \frac{0.2}{3}\right]$$

$$= 0.22\ \mu F = C_{23} = C_{31}$$

b) $$C_N = C_s + 3\ C_C = 0.2 + 3 \times 0.08$$

$$= \mathbf{0.44}\ \mu\mathbf{F}$$

c) $$V_{ph} = \frac{V_{line}}{\sqrt{3}} = \frac{11\text{ kV}}{\sqrt{3}} = 6.3508\text{ kV}$$

$$f = 50\text{ Hz}$$

$$\therefore \quad I = \omega C_N V_{ph} = 2\pi \times 50 \times 0.44 \times 10^{-6} \times 6.3508 \times 10^{3}$$

$$= \mathbf{0.8778\ A} \qquad \text{... Charging current}$$

3.12.2 Capacitance of Three Core Cable

There is one empirical formula to calculate the capacitance of a three core belted cable, stated by Simon. It is applicable for the circular conductors. The formula gives the capacitance of a three core cable to neutral per phase per kilometre length of the cable. The formula is given as,

$$\boxed{C_N = \frac{0.0299\,\varepsilon_r}{ln\left[1 + \frac{T+t}{d}\left\{3.84 - 1.7\frac{t}{T} + 0.52\frac{t^2}{T^2}\right\}\right]}\ \mu F/km}$$

where. ε_r = Relative permittivity of the dielectric

d = Conductor diameter

t = Belt insulation thickness

T = Conductor insulation thickness

The formula can be used when the test results are not available. This gives approximate value of the capacitance. If ε_r is not given, it can be assumed to be 3.5. It must be remembered that all the values of d, t and T must be used in the same units while using the formula.

Example 3.11 : *A three core cable has core diameter of 2 cm and core to core distance of 4 cm. The dielectric material has relative permittivity of 5. Compute the capacitance of this cable per phase per km. Thickness of the conductor insulation is 1 cm and that of belt insulation is 0.5 cm.*

Solution : d = 2 cm, ε_r = 5, T = 1 cm, t = 0.5 cm

The angle ϕ_d is the power factor angle of dielectric.

$$\cos \phi_d = \cos (90-\delta) = \sin \delta$$

It depends on the temperature and voltage stress to which dielectric is subjected.

3.13.3 Sheath Loss

In a.c. transmission, alternating currents flowing through the cable produce pulsating magnetic field. This electromagnetic pulsating field links with the lead sheath and induces current in it. The value of this current depends on the frequency of pulsating field, sheath resistance, arrangement of cables and sheath conditions whether it is bounded or unbounded. These sheath currents produce the sheath losses.

There are two types of currents in the sheath,

1. Sheath eddy currents having both inword and outword directions and flow totally in the sheath of same cable.

2. Sheath circuit currents which flow from sheath of one cable to the sheath of other cable.

The unbounded cable means having one end or no ends, electrically shorted hence sheath circuit currents are absent in unbounded cable. The bounded cables means the two different cables have a sheath electrically connected at both the ends hence both the types of currents are present in them.

The approximate formula to calculate sheath losses due to sheath eddy currents is suggested by Arnold as,

$$\boxed{\text{Sheath loss} = I^2 \left\{ \frac{3\,\omega^2}{R_s} \left(\frac{r_m}{d} \right)^2 \times 10^{-18} \right\} \quad \text{W/cm/phase}}$$

where I = Current per conductor in Amp

r_m = Mean radius of sheath

R_s = Sheath resistance in Ω

d = Spacing between conductors

These losses are practically very small and hence generally neglected.

Key Point : *Thus core loss, dielectric loss and sheath loss together constitute to the heating of the cables.*

3.14 Heat Flow in a Cable

As seen earlier, the current in the cable, dielectric loss and sheath loss together cause the increase in the temperature of the cable. The heat produced due to increase in temperature must be dissipated to the soil. When rate of heat generation and dissipation becomes equal then temperature becomes constant. This temperature infact is the important factor for deciding current carrying capacity of the cable.

The thermal resistivity is expressed in °C/watt/cm

Consider the equivalent circuit for heat flow in a three phase cable as shown in the Fig. 3.30.

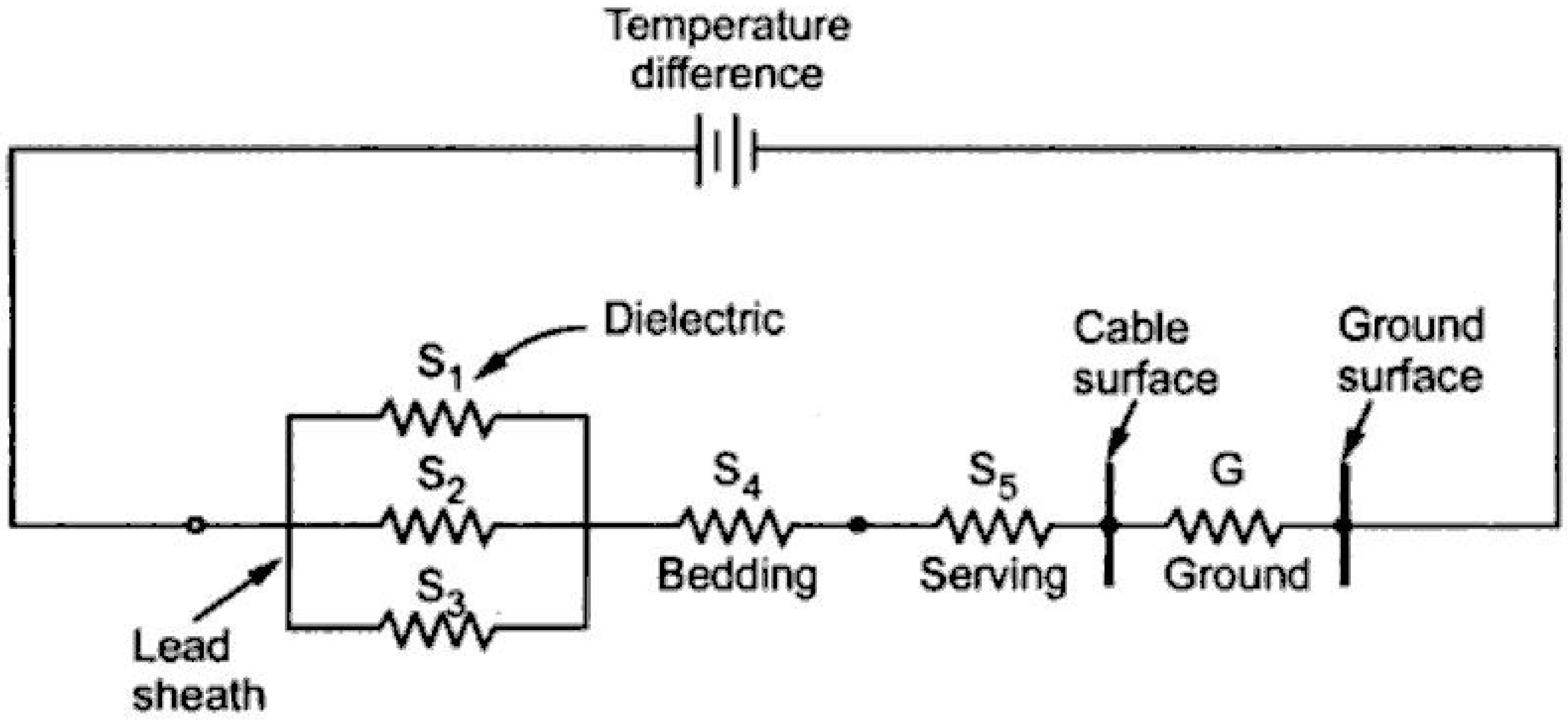

Fig. 3.30

The total temperature difference is difference between conductor temperature and ambient temperature. The S_1, S_2 and S_3 are thermal resistances of the three dielectric paths which are in parallel. Then heat flows through bedding whose thermal resistance is S_4. Finally it flows through serving whose thermal resistance is S_5. The G represents the thermal resistance of ground to ambient temperature. The current carrying capacity of cables depends on the heat dissipation and to calculate it, it is necessary to obtain the thermal resistances of various parts through which heat flows.

3.14.2 Thermal Resistance of Single Core Cable

Consider a single core cable as shown in the Fig. 3.31. Let

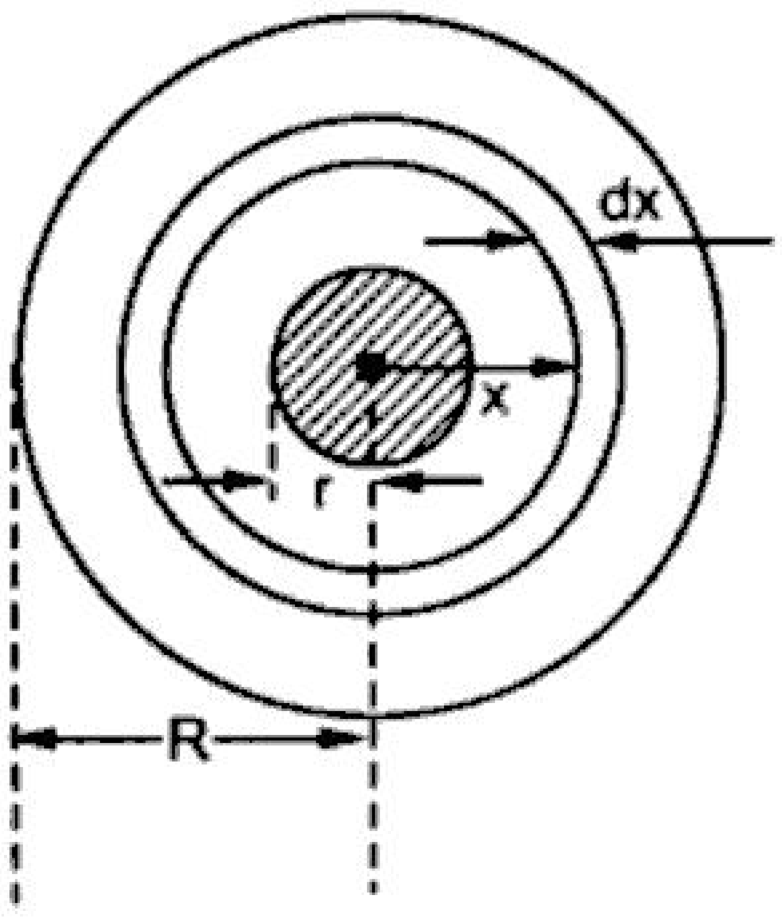

Fig. 3.31 Single core cable

r = Core radius

R = Overall radius

l = Length

k = Thermal resistivity

$$ds = \frac{k\,dx}{A}$$

$$\therefore \quad ds = \frac{k\,dx}{2\pi x \times l} \quad \text{as } A = \text{Surface area}$$

$$\therefore \quad S = \int_r^R \frac{k\,dx}{2\pi x l} = \frac{k}{2\pi l}\int_r^R \frac{dx}{x} = \frac{k}{2\pi l}[ln\, x]_r^R$$

$$\therefore \quad S = \frac{k}{2\pi l}\, ln\, \frac{R}{r} \quad \text{thermal ohms}$$

$$\text{i.e.} \quad S = \frac{k}{2\pi}\, ln\, \frac{R}{r} \quad \text{thermal ohms/m}$$

3.16.1 Murray Loop Test

In this test, the principle of Wheatstone's bridge is used to locate the ground faults. In ground fault, one or more cable cores get earthed. This is the most accurate test.

In this test, one sound return wire of the same cross-section as that of cable is required. The connections are shown in the Fig. 3.32.

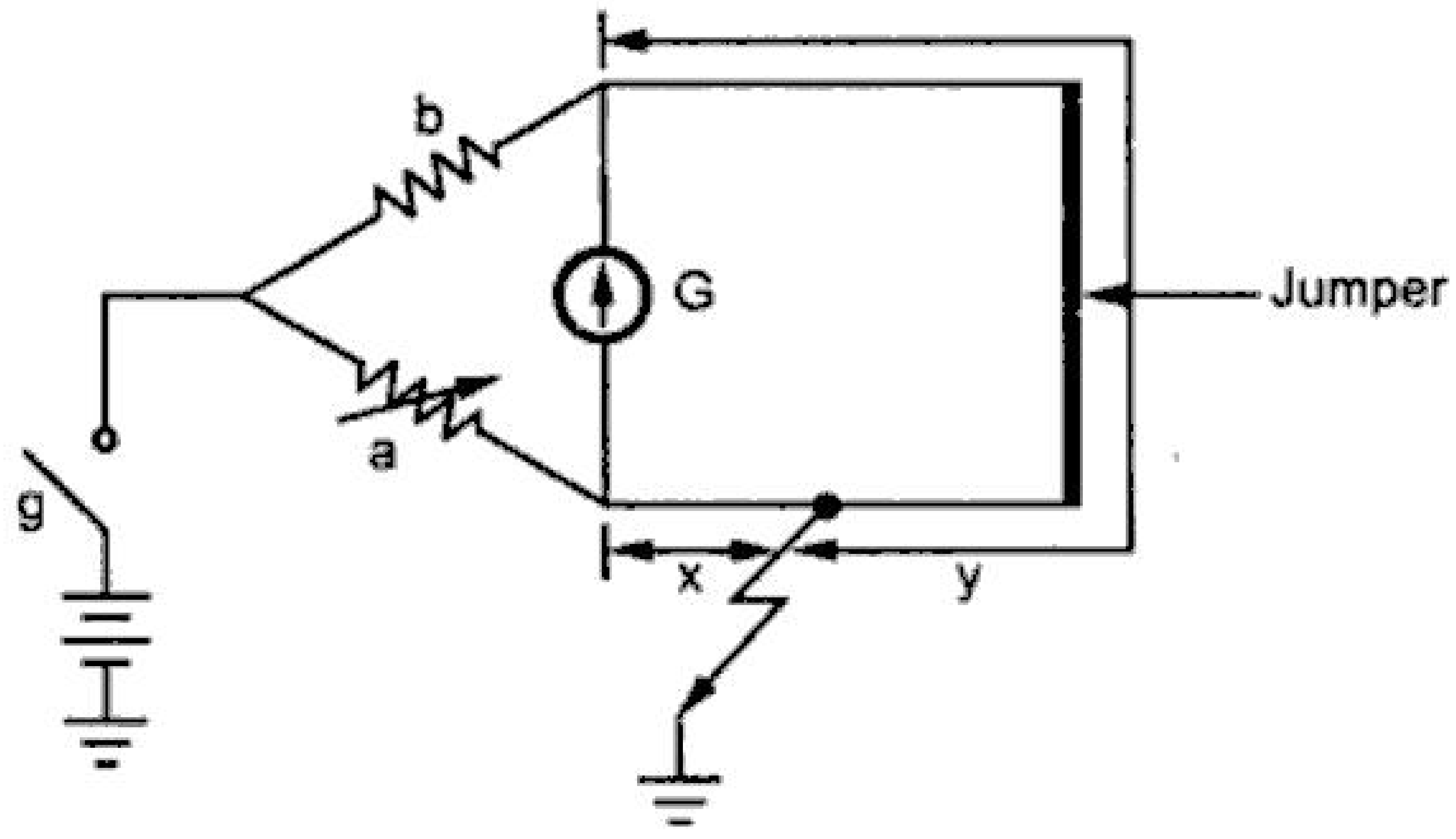

Fig. 3.32

The perfectly sound cable is looped with faulty cable. The balance of the bridge is obtained by varying the resistances.

The distance of the fault is given by,

$$\boxed{d = \frac{a}{a+b} \times \text{Loop length}}$$

where a = Resistance connected to faulty cable

b = Resistance connected to sound cable

Loop length = x + y i.e. 2 times the route length

3.16.2 Fall of Potential Test

The arrangement used for the test is shown in the Fig. 3.33.

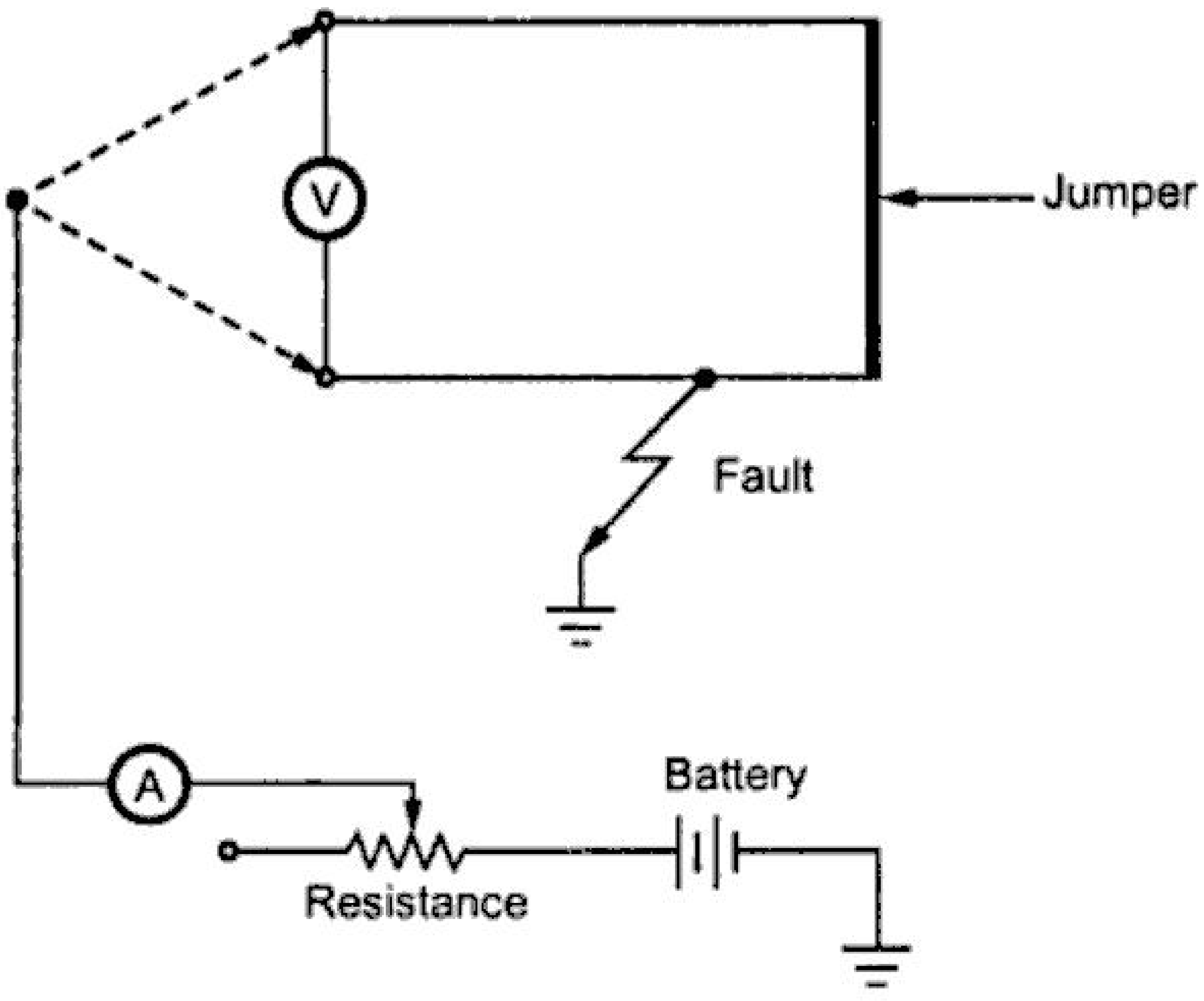

Fig. 3.33 Fall of potential test

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